PUBLIC REPORT PPS PROJECT: PANGEA

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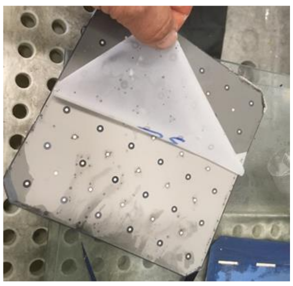
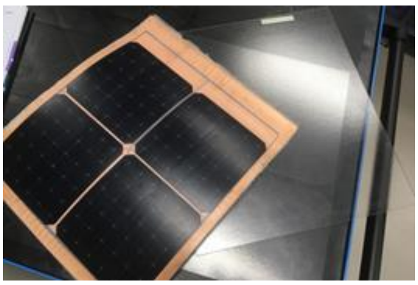
www.tki-urbanenergy.nl





SUMMARY

The cumulative installed photovoltaic (PV-panel) capacity in the Netherlands has reached 14 GWp by 2021. With a further rapid increase of PV power an annual volume of PV waste of more than 200.000 tons/year is forecasted by 2045, making clear that adequate solutions for PV-panel end-of-life management are needed.

The aim of this project is to develop methods to prepare PV panels for re-use at end-of-life, turning waste into a useful product again. This will be approached by rebuilding of new PV panels based on components recovered from end-of-life PV panels.

In a practical approach TNO will rebuild new PV panels from disassembled PV panel components by introducing a so called release encapsulant. This material enables easy disassembly of PV modules at end-of-life. Different generations of encapsulant materials are developed by The Compound Company (TCC) and evaluated considering integration into PV panels, fast release functionality and the quality requirements important to application in PV panels: power output and durability. The release encapsulant also enables exchange of solar cells before end-of-life if higher efficiency cells become available. TNO evaluated the environmental benefits of the release encapsulant and material re-use potential for PV panel production by means of life cycle assessment studies (LCA).

Disassembly of PV modules equipped with release encapsulant proved to be successful resulting in harvesting clean glass plates featuring the same transmission characteristics as in the original state. Adhesion testing showed that the release encapsulant materials adheres sufficiently to the different surfaces relevant for the different PV components. By introducing a fast release encapsulant the disassembly process could be accelerated by a factor 2.

Lifetime testing of PV modules equipped with release encapsulant proved to be successful in case of well-sealed undamaged devices. Devices featuring cracks in the glass suffered from degradation due to moisture ingress. Given the fact that the encapsulation material itself has a relatively high moisture permeability a proper moisture blocking edge sealant has been successfully applied to prevent moisture ingress from the module edges. These result open the way to validating of this novel material for application in PV modules considering reliability aspects in view of typical environmental stress factors such as moisture, heat and temperature changes.

The LCA study assessed the environmental performance of three Silico hetero junction (SHJ) photovoltaic system configurations under current European conditions. The results show that repowering strategies can significantly reduce impacts per unit of electricity generated when evaluated over extended lifetimes of 90 years. A scenario based on integrating higher-efficiency cells, consistently achieves the lowest impacts across most categories due to improved lifetime energy yield.

The analysis confirms that single-crystalline silicon wafer production is the dominant contributor across multiple impact categories, particularly climate change, ionizing radiation, non-renewable energy use, and water consumption. Additional contributions arise from metallization paste, aluminum production, inverter manufacturing, and integrated circuit fabrication. Electricity consumption in energy-intensive processes remains the principal environmental driver.

The break-even analysis demonstrates that the environmental benefits of repowering are strongly dependent on total operational lifetime. While repowering reduces impacts at 90 and 60 years, it becomes environmentally unfavorable at 45 years. This indicates that lifetime extension and sustained performance are critical conditions for circular design strategies to deliver measurable environmental improvements.

End-of-life recycling was excluded due to a lack of robust data, and no recycling credits were applied. Therefore, the results reflect cradle-to-use impacts and do not account for potential future material recovery benefits. This boundary choice ensures transparency but also indicates that further research is required to evaluate the full circular potential of advanced SHJ modules. Repowering SHJ photovoltaic systems offers substantial environmental advantages when long-term operation is guaranteed and degradation is effectively managed. However, the environmental superiority of such strategies is contingent upon system longevity, stable performance, and the carbon intensity of upstream wafer production. Future decarbonization of silicon manufacturing and improved end-of-life data availability will be decisive in further enhancing the sustainability of SHJ photovoltaic technologies.

The environmental performance of the repowering scenarios assessed in this study is based on current conditions, and two prospective developments could further reduce the breakeven lifetime. In particular a repowered SHJ panel dismantled every 30 years, reusing structural components and replacing original cells with higher-efficiency cells for improved performance. First, while end-of-life recycling was excluded from the present system boundary due to insufficient infrastructure data, the 30-year operational cycles modelled align with the timeframe over which dedicated recycling pathways for SHJ modules are likely to mature. The European FRELP (Full Recovery End-of-Life Photovoltaic) process has demonstrated silicon recovery rates of 95% from crystalline silicon PV panels through mechanical and chemical treatments, while the ROSI (Return of Silicon) process employs thermal and chemical separation methods to recover ultra-pure silicon suitable for reintegration into solar and semiconductor manufacturing. If future recycling infrastructure enables silicon recovery from dismantled cells at these demonstrated efficiency levels — extracting and reprocessing the silicon material with lower environmental burden than virgin Czochralski silicon production — then the manufacturing impact of replacement cells in the repower kit would be substantially reduced. Since single-crystalline wafer production currently dominates the carbon footprint across all scenarios, reducing this burden through silicon material recovery would lower the cumulative embodied emissions, shifting the breakeven point to an earlier lifetime than the approximately 52 years identified here. Second, the present study models upstream electricity consumption using a 2020 European electricity mix. Prospective scenarios incorporating a progressively decarbonized grid — consistent with European energy transition trajectories over the coming decades — would reduce the climate intensity of energy-intensive processes such as single-crystalline wafer production and cell processing. A greener electricity mix would lower absolute emissions for both the initial manufacturing phase and each repowering cycle, further improving scenarios those with additional manufacturing events described in chapter 4.

1 INTRODUCTION

Solar panel recycling is technologically complex due to the layered and highly integrated use of materials. At the same time, the European playing field for panel recycling is still undergoing rapid development, with a variety of initiatives and regulations. Current regulations are primarily focused on quantitative recovery targets (% of total weight) and offer little to no incentives for technology development and recovery of constituent materials from PV panels. Against this background, TNO aims to improve quality rather than quantitative recycling by an innovative development of a release encapsulant to disassemble PV panels based on Design for Recycling technologies. To access the active layers for circular use, TNO applied a release encapsulant that had been developed for PV panels, which allowed the separation of these panels into single components (encapsulant, interconnected cells, rear and front glass/back sheet). In the long run the elaborated technology in this project supports future policy choices and market potential for solar panel recycling in a European context. In a wider framework, the activities described in this report are in conjunction with current policy frameworks by the European Community and the Netherlands in 2025.

The focus is on three pillars:

- Strategic Relevance: Reducing import dependency through domestic extraction and Processing of critical raw materials (e.g. via the CRMA). This addresses the silicon material.
- Circular Economy: Maximising reuse and recycling, supported by innovations such as the Digital Product Passport and national research and innovation programmes.
- Innovative Collaboration: Collaboration between government, knowledge institutions and industry to make the entire value chain — from design to end-of-life — future-proof.

With the results of this work the project partners subscribe to the European Policy Framework:

- Critical Raw Materials Act (CRMA): Regulation for 2030 targets in the extraction, Processing and recycling of critical raw materials.
- Binding benchmarks: minimum 10% EU extraction, 40% processing and 25% recycling; reduction of dependence on a single source.
- RESourceEU (December 2025): the European cooperation platform that promotes ecological circularity goals and increasingly focuses on strategic autonomy in raw material chains, in line with the European Commission's policy priorities.
- EU Energy and Raw Materials Platform (July 2025) - a European Commission instrument to facilitate joint procurement, demand aggregation and matchmaking of energy products and strategic raw materials, with a view to strengthening industrial competitiveness, decarbonisation, security of supply and diversification of supply chains.
- Net Zero Industry Act (NZIA): EU regulation to promote clean technology production within the EU, including value chain support for PV panels and components.
- Nationale Grondstoffenstrategie (NGS): Nederlandse routekaart voor bijdrage aan CRMA-doelen en nationale circulariteitsinspanningen.
- Nationaal Programma Circulaire Economie (NPCE 2025): Circulariteitsdoelen richting 2035, waaronder hogere recycling (55% grondstoffen uit secundair of bio-based in 2035)- en het primaire grondstoffen verbruik met 15% verminderen in 2035.
- Nederlands Materialen Observatorium (NMO): Operationele monitoring van leveringsrisico's en waardeketens van kritieke grondstoffen (sinds februari 2025). tno.nl/nl
- Nationale technologie strategie (jan 2026): inclusief actie agenda procestechnologie.

Pangea entails rebuilding of new high quality circular PV panels made from decommissioned panels. Along the way of gaining practical dismantling and reassembly experience, development of fast release encapsulant is propagated taking into account the environmental impact, resource efficiency and circularity potential.

As a starting point, in a practical approach TNO rebuild new PV panels from disassembled PV panel components by introducing a release encapsulant. This encapsulant enables easy disassembly of PV modules at end-of-life. Several generations of encapsulant materials were developed and evaluated considering integration into PV panels, fast release functionality and the quality requirements important to application in PV panels, power output and durability. The release encapsulant also enables exchange of solar cells before end-of-life if higher efficiency cells become available. TNO evaluated the environmental benefits of the release encapsulant and material re-use potential for PV panel production by means of life cycle assessment studies (LCA).

1.1 Objective

A key enabler to access the PV panel components is a release encapsulant developed and tested in the former TKI projects DEREC and PARSEC. Based on the results of these former projects and with hindsight to industrial processing the release encapsulant has to be optimized for timely release to guarantee fast dismantling capability, within boundaries set by reliability requirements. One of the central aims within this project is to further develop the existing release encapsulant in combination with release accelerating additives.

A major target of the Pangea project is to design a re-use PV panel and support reassembly options retrieved from components of former PV panels. Reassembly is enabled by the release encapsulant opening up routes towards easy and residue free PV panel dismantling.

These reassembled PV panels provide an impetus on demonstrating a new circularity technology based on recovered materials from decommissioned PV panels and novel repowering options. The project aims to re-use the glass front and rear glass sheets.

TNO's target is to design a panel allowing for exchange of the solar cells after several years of panel service to keep up with improvements in cell technology. Exchanging solar cells and replacing them by higher efficient cells enhances return of investment over time and improves the overall performance of a system without changing the original surface area.

To enable the paradigm shift from a linear to a circular production model for PV panels project TNO aims to evaluate the environmental benefits of the release encapsulant and material re-use potential for the TCC circular PV panel production. This requires analyses of materials and corresponding process flows using life cycle assessment (LCA) methods. The potential environmental benefits by re-using PV panel materials and therefore reducing process energy consumption should also result in cost advantages which have to be demonstrated.

The project partners combined their knowledge and expertise to realize remanufacturing options for end of life PV panels and technologies for re-use of components in an environmentally acceptable way.

To achieve this, the following research questions were addressed:

- Can we dismantle and rebuild a PV panel based on release encapsulant by adding new solar cells with higher efficiencies for repowering;
- To what extent is the functionality of this panel influenced, i.e., what is the power rating;
- Can we sufficiently and timely disassemble the PV panel with a fast release encapsulant in combination with release promoting additives;

- Can remanufactured PV panels survive extensive durability testing, keep functionality, yet not compromise panel performance;
- Can release encapsulant in combination with a 100% recyclable backsheet fulfill requirements for reassembly of a recycled PV panel;
- Can we demonstrate by an LCA calculation that the energy payback time will be reduced.

Figure 1.1 presents an overview and embedding of the activities related to the Pangea project targets in conjunction with affiliated PV panel circularity projects.

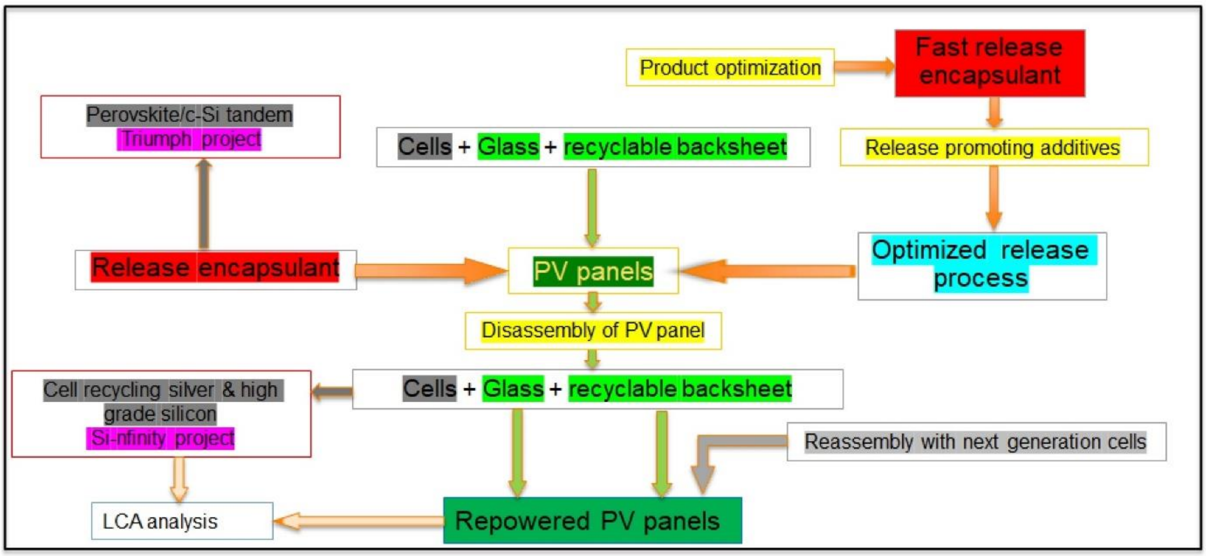
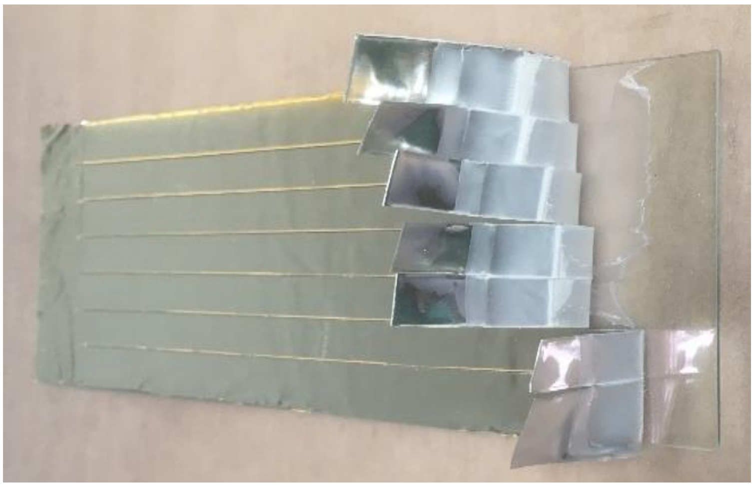


Figure 1.1 *Overview and position of the Pangea project activities in relation with EU Horizon project Triumph and RVO TSE project Si-nfinity.*

2 PV PANEL DISASSEMBLY AND RE-BUILDING WITH COLLECTED MATERIAL

In this work package a release encapsulant was used to manufacture PV modules. Prior to module manufacturing, adhesion tests have been conducted to investigate the optimal combination of material and lamination temperature and select the best performing encapsulant. First material tests were conducted relating to adhesion- or “peel” testing and a typical sample prepared for this test. Figure 2.1 demonstrates the peel test set-up as used for the experiments.

Peel tester setup



Sample after peel testing

Figure 2.1 *The test procedure involves lamination of a flexible sheet of robust material (in this case black EPE) onto a rigid substrate (e.g. glass) and in between the encapsulation material to be tested. Figure 2.2 shows a schematic cross section of a typical test sample*

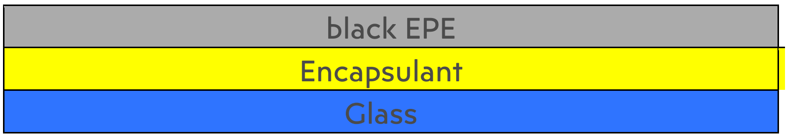


Figure 2.2 *Schematic of a test sample cross section for peel testing*

After lamination the flexible sheet and encapsulant are cut in strips of 1 cm wide. The peel test is conducted by pulling one individual strip at a time from the rigid substrate while measuring the force required to do so. Sufficient adhesion is required for any encapsulation material applied in PV panels to be able to withstand all (thermo-)mechanical stresses experienced in the field. The target value for adhesion is 20N/cm, which means a force of at least 20 N is required to peel off a strip of encapsulant of 1 cm wide from the surface to which it is adhered to. If a cohesive fracture occurs it means that the inner structure of the encapsulant breaks, leaving encapsulant residue on the substrate surface, instead of a proper separation between encapsulant and substrate surface. It implies that the peel force measured is an underestimation of the real adhesion force at the encapsulant-substrate interface. Figure 2.3 shows the adhesion strength of two encapsulant variations at different temperatures.

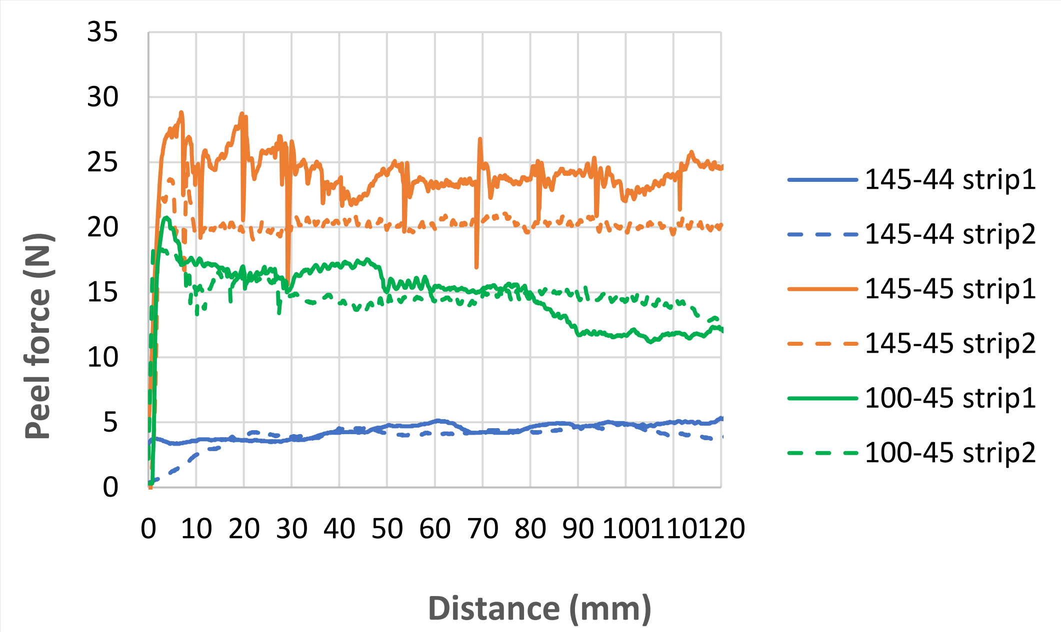


Figure 2.3 *Adhesion strength or peel force of two encapsulant materials (“44”and “45”) on glass for different lamination temperatures*

From Figure 2.3 it can be derived that encapsulant 44 laminated at 145 ˚C has a very low adhesion strength of around 5 N for a 1 cm wide strip. Encapsulant 45 reveals substantially better characteristics: Laminated at a lower temperature of 100 ˚C the adhesion strength already surpasses the 44 laminated at 145 ˚C, to reach an adhesion strength of 20-25 N when also laminated at 145 ˚C. Since the latter sample suffered a cohesive fracture, the value of 20-25 N for the peel strength represents an underestimation of the adhesion strength.

To demonstrate the feasibility of repowering, modules have been build followed by disassembly by means of activating the encapsulant release mechanism resulting in retrieval of intact and clean front- and rear glass plates and broken cells as illustrated in Figure 2.4. The former solar cell was exchanged by a new one and the retrieved front- rear glass plates were used to build a new module successfully. The environmental profile for this process has been evaluated by the LCA analysis in WP4.

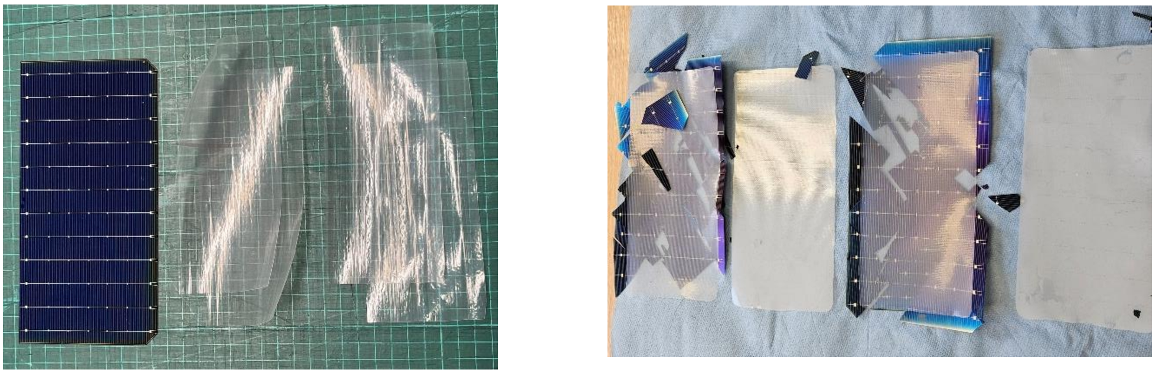


Figure 2.4 *Left: Solar cell and release encapsulant before lamination. Right: Solar cells and encapsulant after lamination followed by release/disassembly.*

Rebuilding a new PV panel with materials recovered from a PV panel which has been taken apart requires separation of the individual materials in a residue free state, in this case that involves the front- and rear glass sheet. Retrieved glass has been analysed regarding surface contamination of encapsulant by means of transmission measurements. When triggered, the release encapsulant readily detached from glass surfaces without leaving any visually observable residue. This is supported by transmission measurements. As shown in Figure 2.5 there is no detectable difference in transmission between untreated glass and glass which has been laminated with release encapsulant followed by the disassembly process. Figure 2.6 shows a small size module based on re-used glass.

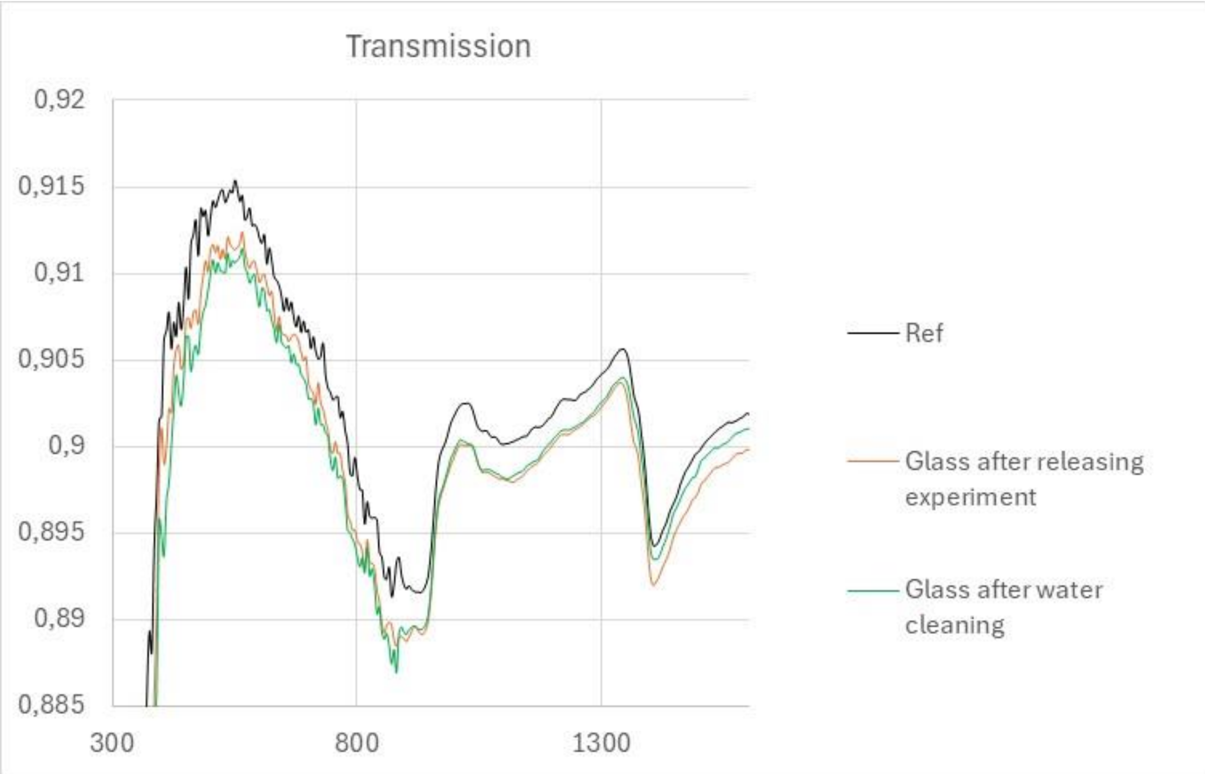


Figure 2.5 *Transmission of retrieved glass from a module compared to unused reference glass just after water cleaning only.*

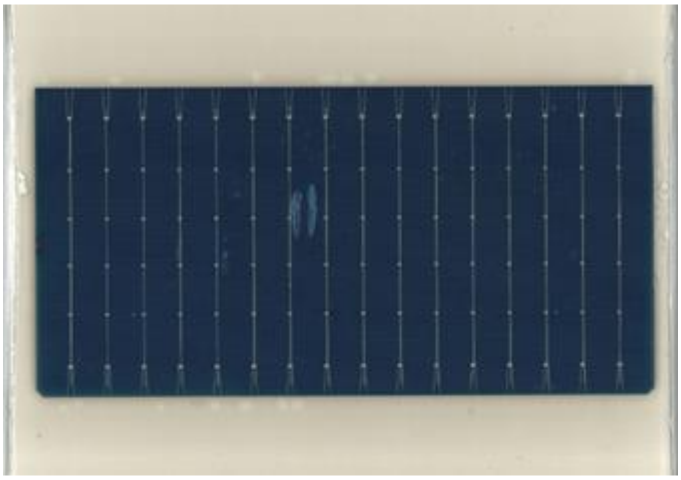


Figure 2.6 *Small sized module based on re-used glass after disassembly of another module.*

To demonstrate the feasibility of further product improvements with respect to speed of release and ease of disassembly The Compound Company manufactured in WP 2 several new varieties of release encapsulant material in order to identify a “fast release” material with improved release properties. For the best performing material the speed of release could be accelerated by a factor of 2, compared to the first generation of materials manufactured at TCC. The “fast release” encapsulant also appears to have a better performance during lamination with respect to material homogeneity as illustrated in the images below (Figure 2.7). The first generation material revealed wrinkles causing local delamination, whereas the fast release variety reveals a very smooth homogeneous appearance after lamination.

First generation of release encapsulant laminated, revealing local delamination

Fast release encapsulant laminated, no delamination

Figure 2.7 *Visual aspects of two generations of release encapsulant after lamination*

Modules manufactured with fast release encapsulant have been successfully dismantled, resulting in clean glass plates ready for re-application in new modules. New modules have been assembled, using these glass plates, and subjected to reliability testing in WP3.

Conclusion WP1:
In conclusion, disassembly of PV modules equipped with release encapsulant proved to be successful resulting in harvesting clean glass plates featuring the same transmission characteristics as in the original state. Adhesion testing showed that the release encapsulant materials adheres sufficiently to the different surfaces relevant for the different PV components. By introducing a fast release encapsulant material developed in WP 2 the disassembly process could be accelerated by a factor 2.

3 WP3 LIFETIME TESTING OF PV MODULE

In WP 3 modules based on release encapsulant have been built and tested in climate chambers to investigate the durability of modules featuring this novel material with respect to environmental factors normally related to field conditions such as temperature and humidity, but then in an accelerated mode. Changes in module performance have been monitored at different intervals by characterization of the electrical output, focussing on changes in fill factor (FF). The fill factor characteristics provide a good indication of the condition of cell contacts and metallization, which are typically prone to degradation induced by moisture or thermal cycling in case of non-matching coefficients of thermal expansion. Device performance was evaluated at different stages of testing. A second indicator for malfunctioning cell contacts is provided by electroluminescence imaging (EL). Electroluminescence imaging has been applied to localize the area’s in which changes occurred. Thermal cycling tests have been executed up to 600 temperature cycles between -40 and 85 ˚C, which is well beyond the requirements (200 cycles) of the IEC 61215 standard. Damp heat testing (minimum 1000 h at 85 ˚C and 85 % relative humidity) is a second important climate chamber test, designed to monitor the effects of moisture ingress. Also by this test mainly metallization and contacts are affected, which becomes visible in FF changes and EL. The test has been executed up to 3000 h, well beyond the requirements of the IEC 61215 standard.

Thermal cycling test (TC)

Figure 3.1 shows the fill factor (FF) characteristics over time during this test.

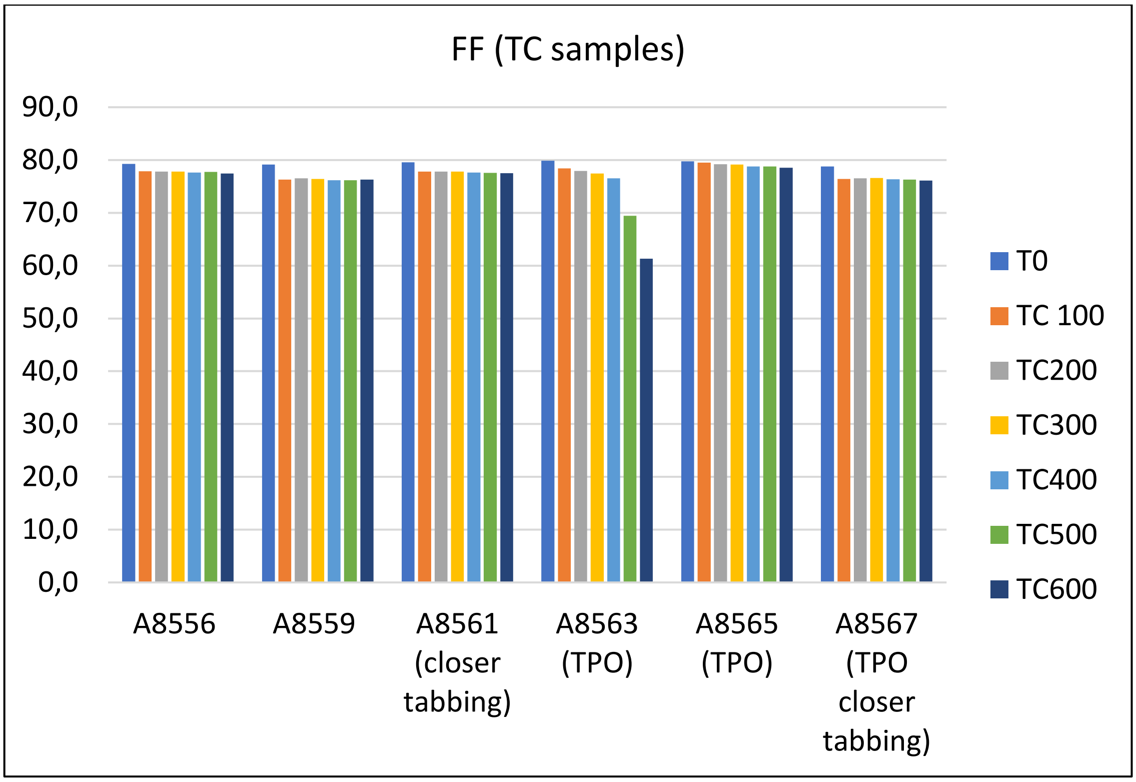
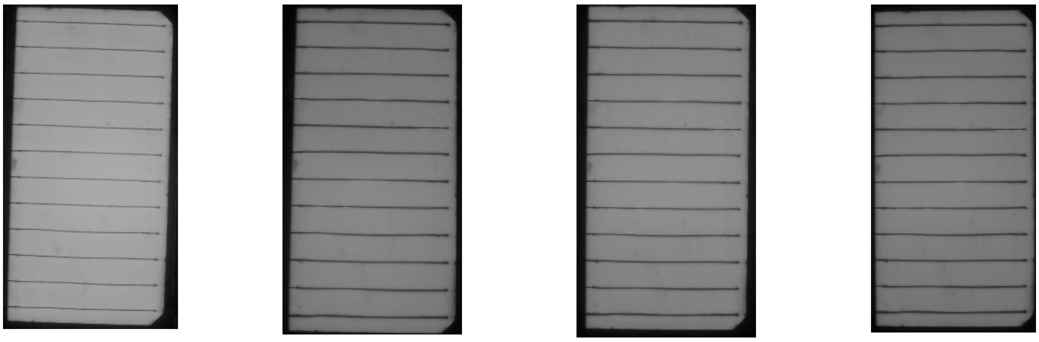


Figure 3.1 *Fill factor of one-cell modules based on release encapsulant at different stages of thermal cycling testing. A8563 has a damaged rear side glass plate.*

From Figure 3.1 it can be derived that the fill factor is stable during thermal cycling testing, with only one exception for a device with damage (a crack in the rear side glass).
Figure 3.2 shows the changes in EL at different stages of the thermal cycling test. For all devices with a stable FF the EL image does not change as shown in Figure 3.2.

TC 8556



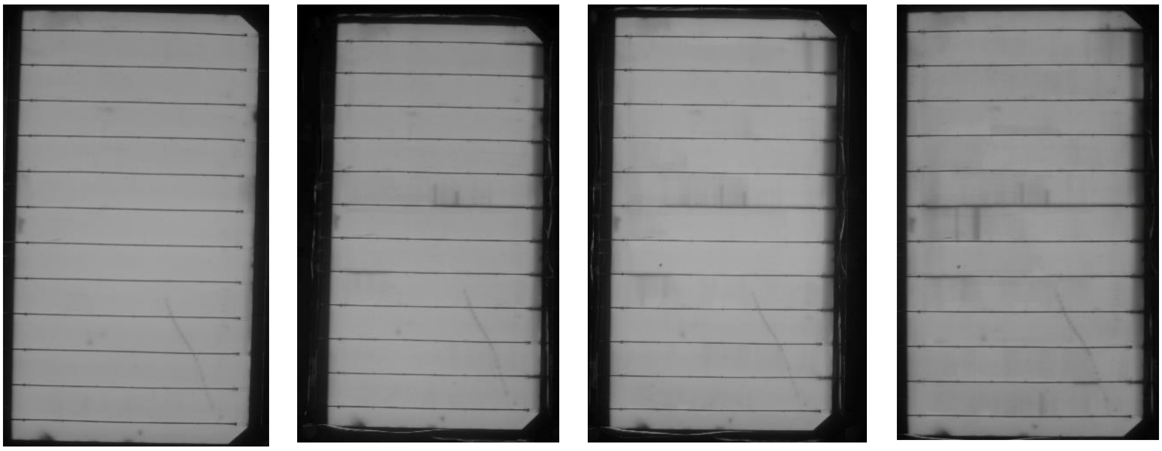
t=0 | 100 cycles | 200 cycles | 300 cycles

400 cycles 500 cycles 600 cycles

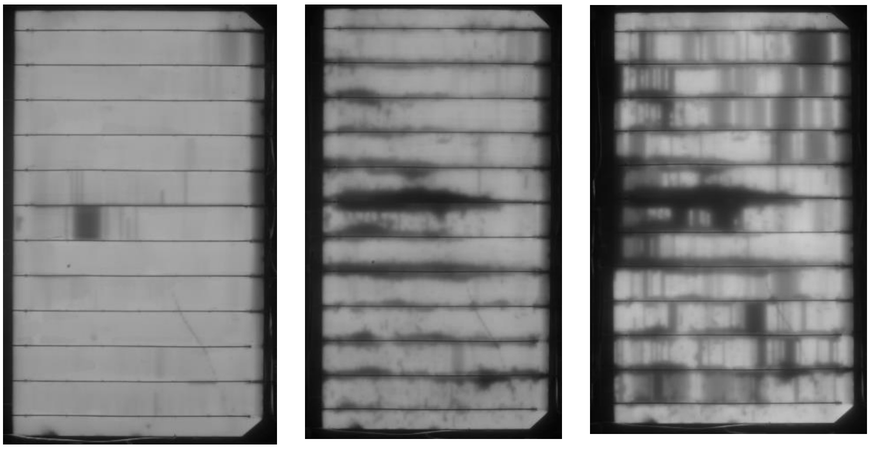
Figure 3.2 Typical EL images for stable one-cell modules at different stages of thermal cycling testing.

The module (A8563) with a crack in the rear side reveals degradation of contacts as indicated by the changes in the EL image during the TC test (Figure 3.3).

TC 8563



t=0 100 cycles 200 cycles 300 cycles



400 cycles 500 cycles 600 cycles

Figure 3.3 Electroluminescence images of a one-cell module (A8563) based on release encapsulant with a damaged rear side glass plate at different stages of thermal cycling testing.

Figure 3.4 shows the FF at different stages of damp heat testing.

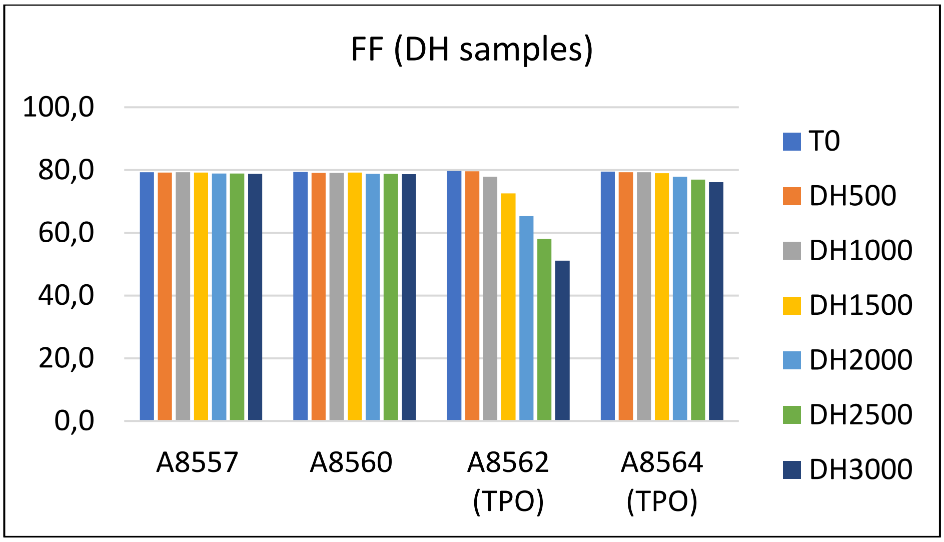
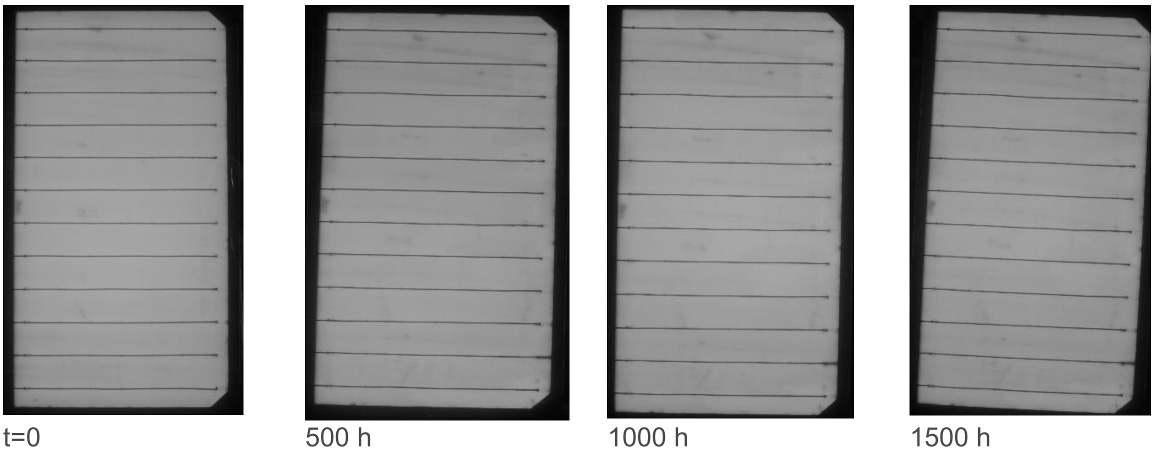


Figure 3.4 Changes in fill factor during damp heat testing. The rear glass of module A8562 cracked during lamination.

From Figure 3.4 it can be derived that for intact modules the FF is stable during damp heat testing up to 3000 h (Figure 3.5), except for one module (A8562) with a crack in the rear glass which provides an entry point for moisture resulting in a loss of FF caused by degradation of metallization. The spreading and effects of moisture through the device can be followed by EL (Figure 3.6) showing increasing dark areas of inactive or less active cell parts affected by degradation of contacts.

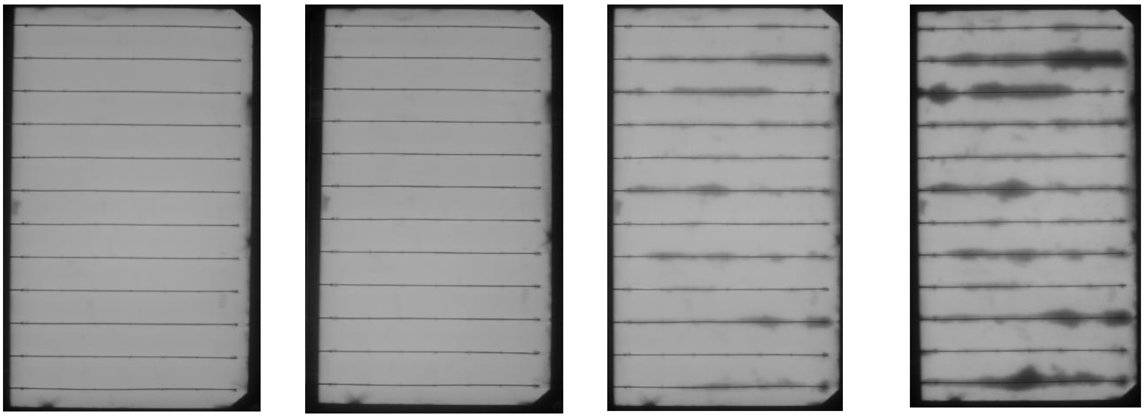
DH A8557



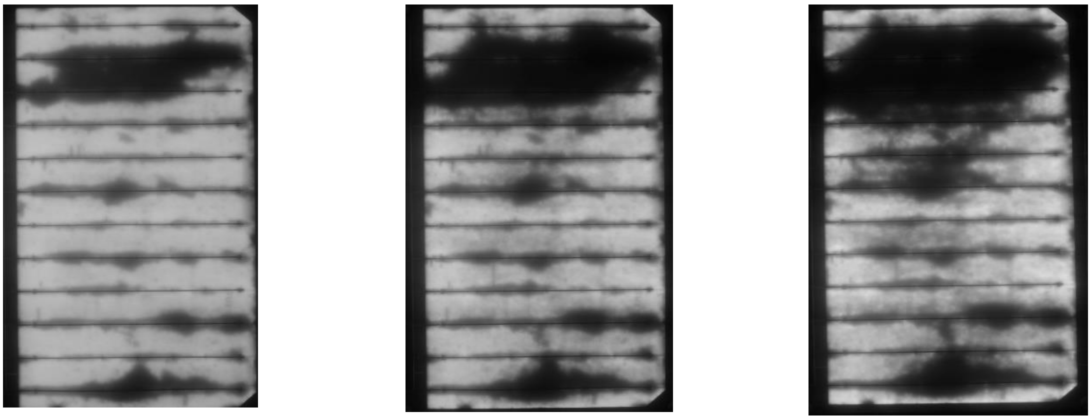
2000 h 2500 h 3000 h

Figure 3.5 *Typical EL images for stable one-cell modules at different stages of damp heat testing*

A8562



t=0 500 h 1000 h 1500 h



2000 h 2500 h 3000 h

Figure 3.6 *Electroluminescence images of a one-cell module (A8562) based on release encapsulant with a damaged rear side glass plate at different stages of damp heat testing*

Modules which have been reassembled by using fast release encapsulant and materials from disassembled modules together with new solar cells have been tested considering reliability in damp heat. Table 3.1 shows the changes in fill factor and maximum power output.

Table 3.1 *Changes in fill factor (FF) and maximum power output after damp heat testing*

		FF (%)			
module ID	t=0	t=500 h	t=1000 h	dFF DH500 (%)	dFF DH1000 (%)
A8825	79,27	79,39	79,26	0,15	-0,01
A8826	78,92	78,97	78,82	0,05	-0,13
A8827	79,22	79,25	79,07	0,03	-0,19
A8830	78,78	78,85	78,70	0,10	-0,10
		Pm (W)			
	t=0	t=500 h	t=1000 h	dPm DH500 (%)	dPm DH1000 (%)
A8825	3,35	3,35	3,37	-0,07	0,42
A8826	3,46	3,44	3,45	-0,52	-0,28
A8827	3,48	3,45	3,44	-0,88	-1,15
A8830	3,48	3,43	3,44	-1,50	-1,22

From Table 3.1 it can be derived that after damp heat testing the fill factor as well as the maximum power output hardly changed, indicating that the modules based on fast release encapsulant and recycled materials from other modules can be as reliable as modules based on standard virgin materials. This is supported by the observations based on electroluminescence characterization showing no changes after damp heat testing, as illustrated in Figure 3.7

Figure 3.7 *Electroluminescence images of a one-cell modules based on fast release encapsulant and re-assembled glass plates at different stages of damp heat testing*

In conclusion, lifetime testing of PV modules equipped with release encapsulant proved to be successful in case of well-sealed undamaged devices. Devices featuring cracks in the glass suffered from degradation due to moisture ingress. Given the fact that the encapsulation material itself has a relatively high moisture permeability a proper moisture blocking edge sealant has been successfully applied to prevent moisture ingress from the module edges.
A series of modules based on release encapsulant has been built and disassembled successfully. The glass plates have been re-used for the building of another series of modules provided with fast release encapsulant and new cells. These modules have been tested successfully considering reliability. These results open the way to validating this novel material for application in PV modules considering reliability aspects in view of typical environmental stress factors such as moisture, heat and temperature changes.

4 LCA PROTOTYPE DEVELOPMENT AND USER REQUIREMENTS

The environmental benefits of the repowered solar module designs using release encapsulant were compared with the state of the art technology. This was done based on the life cycle assessment approach of the ISO standard 14044.

4.1 Life cycle assessment

This section will provide a detailed overview of the life cycle analysis methodology applied. It will outline all the steps involved in conducting a life cycle assessment, including goal and scope definition, inventory analysis, impact assessment, and interpretation. The LCA framework follows the ISO 14044 standard. (ISO, 2022).

4.1.1 Goal and scope definition

Goal definition

The objective of this study is to perform a life cycle assessment (LCA) of a glass–glass (G–G) silicon heterojunction (SHJ) photovoltaic module representative of European production conditions in the year 2020. The assessment focuses on module manufacturing and the use phase, with particular attention given to the integration of circular design strategies, specifically the use of a release encapsulant to enable residue-free dismantling and component reuse. The first goal of the study is to quantify the environmental impacts associated with this novel circular SHJ configuration across multiple impact categories, including climate change and other relevant midpoint indicators, under realistic European production and operational assumptions. The second goal is to compare the environmental performance of this circular design with that of a conventional benchmark SHJ module without circular integration. By evaluating both systems on a consistent functional unit basis, the study assesses whether repowering strategies, component reuse, and lifetime extension result in measurable reductions in environmental impacts across various impact categories. The third goal is to identify environmental hotspots within the life cycle of SHJ photovoltaic modules. Through detailed contribution analysis, the study determines which materials and processes—such as single-crystalline wafer production, metallization paste manufacturing, glass production, aluminium frame and mounting structures, and inverter electronics—dominate overall impacts.

This analysis will quantify the potential benefits of extending panel service life, reducing demand for energy-intensive components, and the potential impacts of the repowered solar panel compared with conventional "one-life" panel designs.

The chosen functional unit is 1 kWh of electricity generated by an SHJ PV module over its operational lifetime. Three system configuration are considered:

- A conventional SHJ panel operated without dismantling, repowering, or component reuse, hereby referred to as S1.
- A repowered SHJ panel dismantled every 30 years, reusing structural components and replacing cells with same-efficiency cells using a release encapsulant, hereby referred to as S2.
- A repowered SHJ panel dismantled every 30 years, reusing structural components and replacing original cells with higher-efficiency cells for improved performance, referred to as S3.

For the repowered scenarios, two replacement cycles are considered, each happening at a 30-year mark. Thus, the total lifetime for the scenarios S2 and S3 is 90 years in comparison with the 30-year lifetime for the S1 scenario.

Scope definition

The temporal scope of this study is defined as the year 2020, representing current production technologies, electricity mixes, and industrial practices within Europe. All foreground processes, including module assembly, dismantling operations for repowering, and photovoltaic cell replacement, are modeled according to the representative industrial conditions of 2020. Energy demand for wafer manufacturing, cell processing, module lamination, aluminum frame production, and inverter manufacturing reflects contemporary industrial data aligned with the current average European electricity mix.

Geographically, the assessment focuses on Europe for both production and operation. Foreground activities such as module assembly, encapsulation, dismantling, and repowering interventions are assumed to occur in European manufacturing facilities. Background processes, including silicon purification and Czochralski crystal growth, silver mining and refining for metallization paste, aluminum smelting, copper production, and integrated circuit fabrication, are assumed to be sourced and modeled using European datasets where available, based on the IEA task 12 (Frischknecht, Stolz, Krebs, Scholten, & Sinha, 2020).

The system boundary includes raw material extraction, material processing, component manufacturing, module assembly, repowering interventions, and the operational use phase, including the mounting system and the inverter. The use phase is evaluated under average European irradiation conditions and standard testing conditions, incorporating realistic performance ratios and degradation rates representative of European installations. Repowering cycles in Scenarios S2 and S3 are explicitly modeled within this operational timeframe.

End-of-life recycling processes are excluded from the scope of this study due to the lack of sufficiently robust and representative data for large-scale recycling of advanced SHJ modules and associated materials. No recycling credits or avoided burden approaches are applied. As a result, the assessment represents a cradle-to-grave system boundary, without the inclusion of recycling.

As mentioned earlier, scenario S3 includes efficiency improvements based on the ITRPV report. No other background and foreground system changes are used in this study.

4.1.1 System boundary

This study follows a cradle-to-grave approach for all three **SHJ panel configurations**. The following flowchart in Figure 4.1 highlights the system boundary as well as the production processes used for the manufacturing of SHJ technology. All waste, off-gas emissions, effluents, and energy entering and leaving the system are accounted for.

4.1.2 Impact assessment method

The chosen impact assessment method for this study was Environmental footprint 3.1(EF 3.1), which is also the recommended impact assessment method by the European Union for conducting LCA. (Susanna, et al., 2023).

It is part of the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methodologies, developed to ensure harmonized and reliable environmental impact assessments within the EU. EF 3.1 provides a set of impact categories and characterization factors based on the latest scientific developments and policy needs. (Susanna, et al., 2023).

4.2 Life cycle inventory analysis

The life cycle inventory (LCI) for this study was compiled using three primary data sources: the IEA PVPS Task 12 report (Frischknecht et al., 2020), the literature study by Louwen et al. (2015) (Louwen, et al., 2015), and the Ecoinvent database (Wernet, et al., 2016).

4.1.2 Wafer and cell manufacturing

The life cycle inventory for wafer manufacturing, which includes the MG-Silicon production, Poly-Silicon production, CZ silicon production, and the Single-crystalline Si wafering & bricking production, was taken from the IEA PVPS Task 12 report (Frischknecht et al., 2020). The location for the wafer and cell manufacturing was chosen as Europe.

Additionally, the life cycle inventory for cell manufacturing, which includes Wet chemicals process, PECVD process, PVD process, Screen printing metallization process, and a Wet bench line, was taken from the literature study by Louwen et al., **2015** (Louwen et al., 2015).

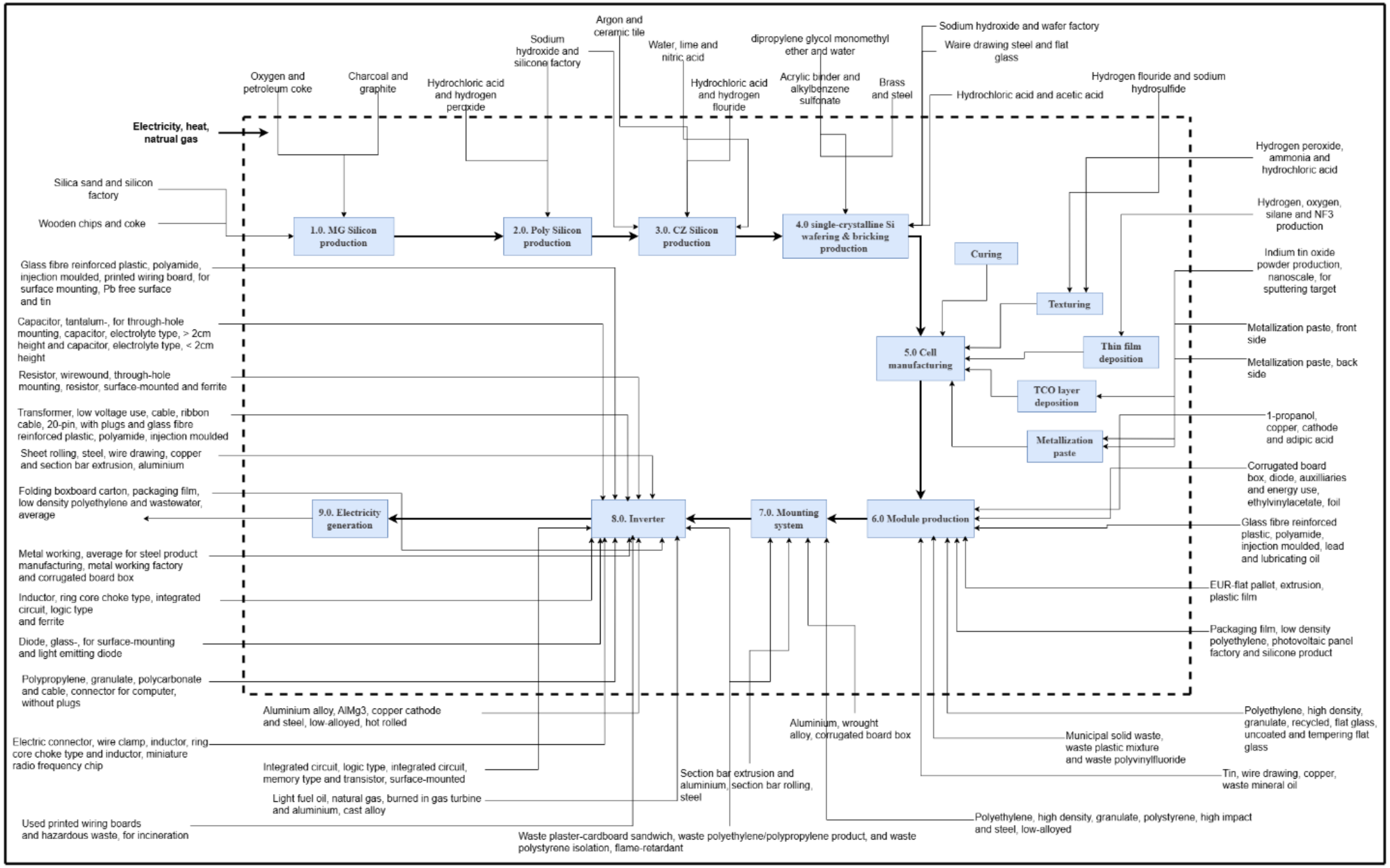


Figure 4.1 *Process flow of the silicon heterojunction (SHJ) photovoltaic system modeled in this study. Blue boxes represent foreground processes explicitly modeled, including silicon production stages, wafering, cell manufacturing, module assembly, inverter production, mounting system, and electricity generation. Processes outside the dashed boundary correspond to background datasets sourced from the ecoinvent database, representing upstream raw material extraction, chemical production, energy supply, and auxiliary material inputs. The dashed lines delineate the system boundary, distinguishing the modeled foreground photovoltaic system from background supply chain processes.*

4.1.3 Module manufacturing

The inventory for module manufacturing was taken from the IEA PVPS report (Frischknecht et al., 2020). The location of manufacturing the modules was set as Europe. Additionally, parameters such as Module efficiency, area, degradation rate, weight, and maximum power were taken from Meyer Burger's spec sheet for glass-glass modules (Burger, 2024). This was done to demonstrate industrial module data. The following table summarises the specifications for the module modelled in this LCA.

Table 4.1 Module parameters for the glass-glass modules taken from (Burger, 2024).

Module parameter	Glass- glass module Value (based on M10 Meyer Burger module)
Efficiency	21.8%
Area	1.95 m^2
Lifetime	30 years
Weight	24.4 kg
Maximum power	390 kWp
Degradation rate	1% degradation in 1^{st} year; 0.2% annual degradation
Irradiance rate	1000 W/m^2

This study aims to evaluate the environmental implications of repowering PV panels, that is, replacing the original solar cells with newer, higher-efficiency cells every 30 years while reusing the glass, backsheet, frame, and encapsulant. For this, the ITRPV report is used for the increase in efficiency of solar cells assumption, which claims an increase to 24% efficiency for SHJ PV in the next 10 years (ITRPV, 2025).

4.1.4 Use phase

Within the use phase, the inventory for the inventor and the balance of the system were taken directly from the IEA PVPS report (Frischknecht et al., 2020). A fixed mounting system without tracking was assumed for this study.

Additionally, all the data collected in this study were normalized to a 1 m² module area and subsequently converted to the generation of 1 kWh of electricity, which serves as the functional unit of this analysis. The conversion from 1 m² to 1 kWh was carried out based on the parameters summarized in table 4.1.

The equation used for making this conversion calculation from $1m^2$ to 1kWh is as follows:

$$Lifetime\ energy\ generation(E)\ per\ m^2 = \eta * PR * Irr * LT * Area * DR$$

Where η = efficiency of the module, PR= performance ratio, Irr= irradiation rate, LT= lifetime and DR= average degradation rate.

The following paragraph will highlight the changes in the degradation rate over the lifetime of the three system configurations included in this study.

4.1.5 Degradation rate analysis

The efficiency evolution curves illustrate the fundamental operational differences between the three scenarios.

In Scenario S1, the module operates over a single 30-year lifetime without repowering. Efficiency decreases steadily from 21.8% to approximately 20.3% due to a constant annual degradation rate. Because no performance restoration occurs, degradation losses accumulate irreversibly, resulting in a continuous decline in average operating efficiency.

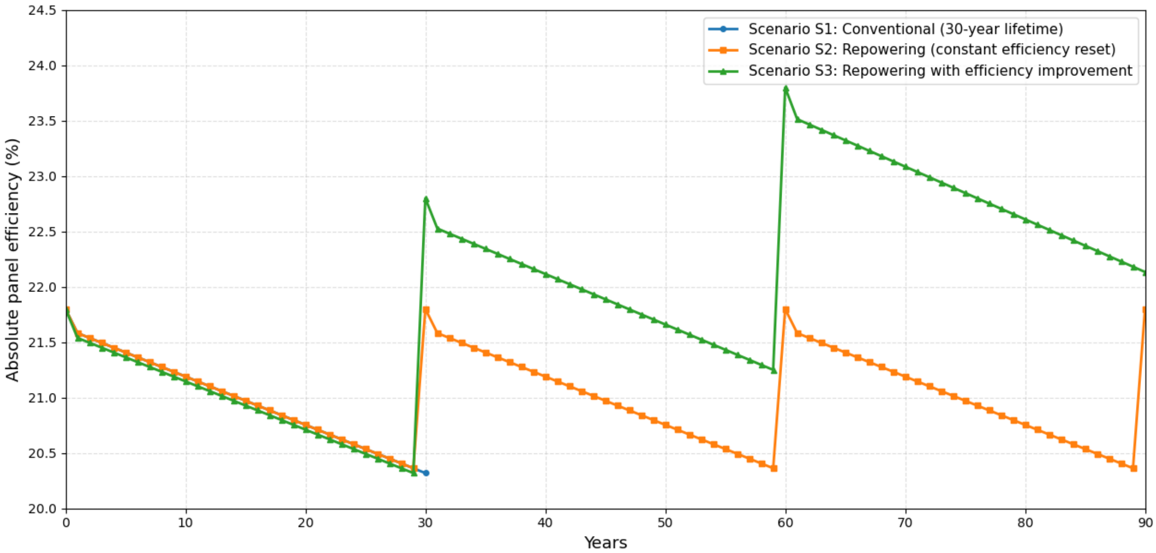


Figure 4.2 *Temporal evolution of absolute panel efficiency (%) over a 90-year period for the three system configurations. Scenario S1 represents a conventional SHJ panel operating for 30 years without repowering, showing gradual efficiency degradation. Scenario S2 illustrates periodic repowering every 30 years with replacement cells of identical efficiency, resulting in efficiency resets while maintaining the same initial performance level after each cycle. Scenario S3 depicts repowering with higher-efficiency cells at each 30-year interval, leading to stepwise efficiency improvements followed by degradation within each operational cycle. The figure highlights the influence of degradation behavior and repowering strategy on long-term energy yield.*

Scenario S2 introduces repowering every 30 years while reusing structural components such as glass and the frame. The efficiency therefore follows a cyclical pattern: linear degradation within each cycle followed by a reset to the initial efficiency upon cell replacement. Although additional cell manufacturing impacts are introduced, periodic restoration prevents long-term performance decline. Over the 90-year lifetime, the average efficiency is 21.008% for Scenario S2, compared to 20.97% in Scenario S1, representing an increase of approximately 0.038 percentage points (≈0.18%).

Scenario S3 further enhances this effect by integrating higher-efficiency cells during each repowering stage. Unlike Scenario S2, where efficiency resets to the original value, Scenario S3 shows progressively higher peak efficiencies at years 30 and 60. Scenario S3 shows a substantially higher average efficiency of 21.92%, corresponding to an increase of 0.95 percentage points (≈4.5%) relative to Scenario S1.

4.2 Results

4.2.1 Impact assessment

Comparison between scenarios

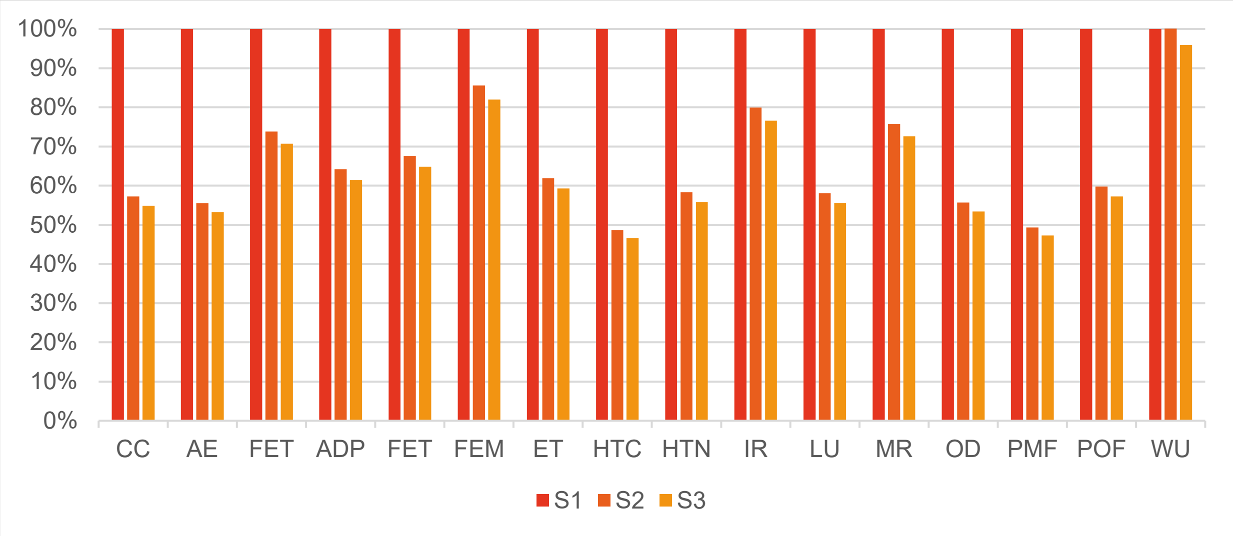


Figure 4.3 Relative comparison of environmental impact categories for the three SHJ photovoltaic system configurations. Scenario S1 is set as the reference (100%) in each category, while Scenarios S2 and S3 are expressed as percentages relative to S1. The impact categories include Climate change: fossil (CC), Acidification (AE), Ecotoxicity: freshwater (FET), Energy resources: non-renewable (ADP), Eutrophication: freshwater (FET), Eutrophication: marine (FEM), Eutrophication: terrestrial (ET), Human toxicity: carcinogenic (HTC), Human toxicity: non-carcinogenic (HTN), Ionizing radiation: human health (IR), Land use (LU), Material resources: metals/minerals (MR), Ozone depletion (OD), Particulate matter formation (PMF), Photochemical oxidant formation: human health (POF), and Water use (WU). Values are normalized to the baseline scenario to facilitate cross-category comparison.

The life cycle impact assessment results reveal consistent and meaningful differences between the three photovoltaic (PV) system configurations: the conventional SHJ panel (scenario S1), the repowered SHJ panel (scenario S2), and the repowered SHJ panel scenario with increased efficiency (scenario S3). Across all midpoint impact categories, a clear pattern is observed in which Scenario S1 consistently exhibits the highest environmental impacts, Scenario S2 shows reductions in comparison to Scenario S1, and Scenario S3 demonstrates the lowest impacts. The following table 3 highlights the same.

A dominant pattern across nearly all environmental indicators is the progressive reduction of impacts from Scenario S1 to Scenario S3. Scenario S1 shows the highest contribution because it represents a conventional single-life module design in which no repowering or component reuse occurs after the operational lifetime. All environmental burdens are therefore associated with the full production of new materials and components, including energy-intensive processes such as silicon cell manufacturing, glass production, and aluminum frame fabrication.

In contrast, Scenario S2 reduces environmental burdens by enabling residue-free dismantling and reuse of key structural components, including glass, frames, and encapsulants, while replacing only the solar cells during repowering. This significantly decreases the demand for virgin material production and lowers upstream manufacturing impacts.

Scenario S3 achieves the greatest environmental benefits. In addition to component reuse similar to Scenario S2, this scenario incorporates higher-efficiency solar cells during repowering cycles, which increases electricity generation over the module lifetime. Because environmental impacts are calculated per functional unit of electricity produced, this higher energy yield further reduces the relative environmental burden.

Table 4.2 Absolute impact assessment values of various impact categories for the scenarios S1, S2, and S3.

Impact category	Abbreviation	Units/kWh	S1	S2	S3
Climate change: fossil	CC	kg CO_2-Eq	3.62E-02	2.07E-02	1.99E-02
Acidification	AE	mol H+-Eq	2.59E-04	1.44E-04	1.38E-04
Ecotoxicity: freshwater	FET	CTUe	8.57E-01	6.32E-01	6.06E-01
Energy resources: non-renewable	ADP	MJ, net calorific value	4.97E-01	3.19E-01	3.06E-01
Eutrophication: freshwater	FET	P-Eq	3.97E-05	2.69E-05	2.58E-05
Eutrophication: marine	FEM	N-Eq	1.39E-04	1.19E-04	1.14E-04
Eutrophication: terrestrial	ET	mol N-Eq	5.91E-04	3.65E-04	3.50E-04
Human toxicity: carcinogenic	HTC	CTUh	9.27E-11	4.51E-11	4.33E-11
Human toxicity: non-carcinogenic	HTN	CTUh	8.30E-10	4.84E-10	4.64E-10
Ionizing radiation: human health	IR	kBq U235-Eq	5.49E-03	4.39E-03	4.20E-03
Land use	LU	dimensionless	2.20E-01	1.28E-01	1.23E-01
Material resources: metals/minerals	MR	kg Sb-Eq	8.53E-06	6.46E-06	6.19E-06
Ozone depletion	OD	CFC-11-Eq	9.01E-10	5.02E-10	4.81E-10
Particulate matter formation	PMF	disease incidence	2.33E-09	1.15E-09	1.10E-09
Photochemical oxidant formation: human health	POF	kg NMVOC-Eq	1.70E-04	1.01E-04	9.70E-05
Water use	WU	m3 world Eq deprived	1.95E+00	1.96E+00	1.87E+00

4.3.2 Interpretation

The following section will highlight the individual contribution of each S1, S2, and S3 scenarios towards the impact categories. For the figures, Scenarios S1 and S3 are demonstrated, considering Scenario S2 and S3 showcase a similar impact reduction across scenarios.

Contribution analysis

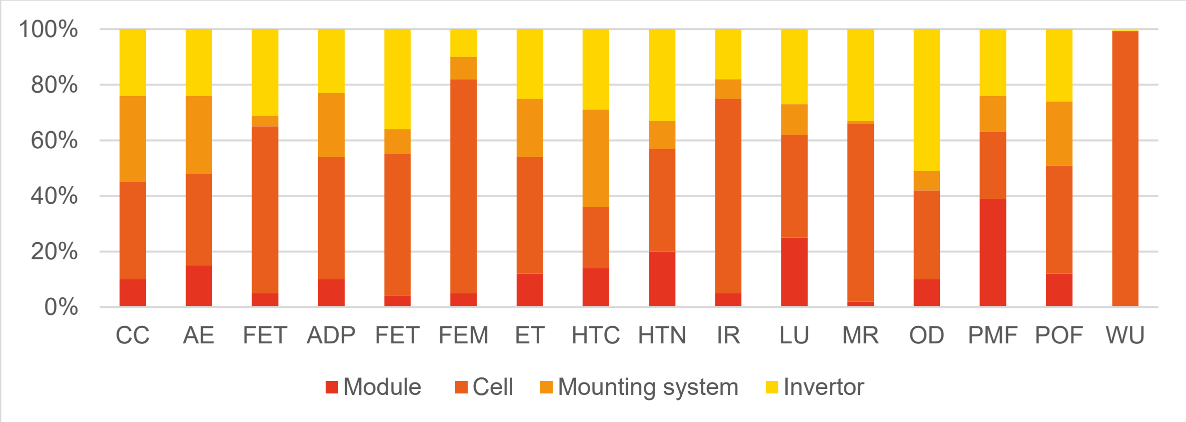


Figure 4.1 *Contribution analysis of Scenario S1 (conventional SHJ panel) across all assessed impact categories. The stacked bars represent the proportional contribution of major system components—module, cell, mounting system, and inverter—to each impact category, including Climate change: fossil (CC), Acidification (AE), Ecotoxicity: freshwater (FET), Energy resources: non-renewable (ADP), Eutrophication: freshwater (FET), Eutrophication: marine (FEM), Eutrophication: terrestrial (ET), Human toxicity: carcinogenic (HTC), Human toxicity: non-carcinogenic (HTN), Ionizing radiation: human health (IR), Land use (LU), Material resources: metals/minerals (MR), Ozone depletion (OD), Particulate matter formation (PMF), Photochemical oxidant formation: human health (POF), and Water use (WU). Each category is normalized to 100% to illustrate relative component contributions within the baseline configuration.*

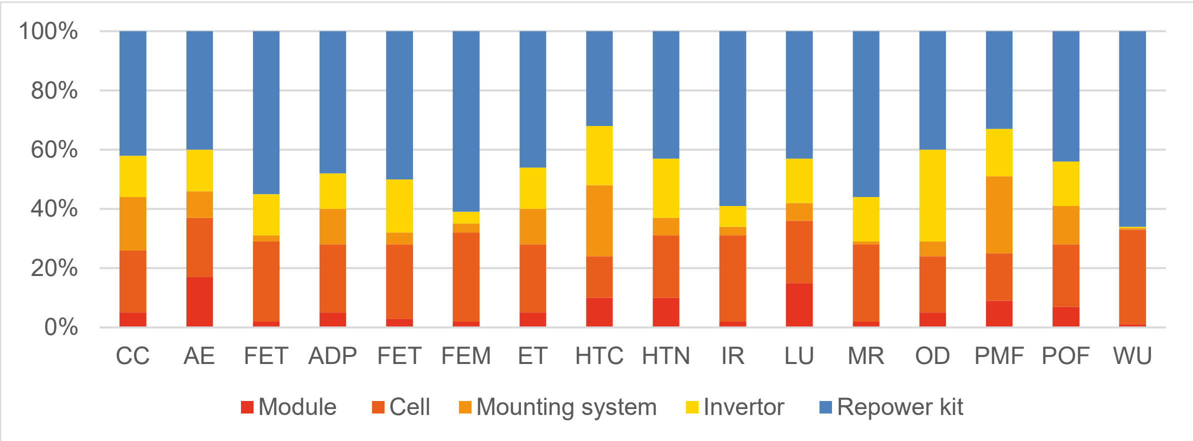


Figure 4.2 *Contribution analysis of Scenario S3 (repowered SHJ panel with efficiency improvement) across the same impact categories. In addition to the module, cell, mounting system, and inverter, the repower kit is included as an additional component to reflect the material and energy inputs associated with periodic cell replacement and repowering interventions. The stacked bars show the proportional distribution of contributions per impact category, normalized to 100%, enabling comparison of structural differences in impact composition relative to the baseline scenario.*

Climate change and non-renewable energy resource

Within the climate change impact category, Scenario S1 exhibits the highest impacts, at approximately 36 g CO_2 eq./kWh. Scenario S2 shows a substantial reduction, with impacts decreasing to about 21 g CO_2 eq./kWh, corresponding to an approximate 42 percent reduction compared to Scenario S1. Scenario S3 demonstrates the lowest impacts, at around 19 g CO_2 eq./kWh, representing an overall reduction of about 47 percent relative to Scenario S1.

Within the non-renewable energy resource category, Scenario S1 shows impacts of approximately 0.50 MJ/kWh, followed by Scenario S2 at about 0.32 MJ/kWh, representing an approximate 36 percent reduction, and Scenario S3 at around 0.31 MJ/kWh, corresponding to an overall reduction of about 38 percent compared to Scenario S1.

Across both categories, the highest contribution towards the impacts arises from solar cell manufacturing, primarily due to high electricity consumption during single-crystalline wafer production. The wafer manufacturing process is particularly energy-intensive and therefore dominates both greenhouse gas emissions and fossil energy demand. This is followed by panel manufacturing components, especially flat glass production and copper use, and by the mounting system due to aluminium production, which also requires high electricity consumption. Inverter production contributes additionally, with major impacts arising from the manufacturing of integrated circuit boards, particularly due to electricity use and gold consumption.

Although Scenarios S2 and S3 include additional impacts from the replacement of solar cells during repowering cycles, these additional burdens are compensated for by the reuse of major structural components such as glass, frames, and encapsulants. Furthermore, extending the operational lifetime from 30 years to 90 years distributes environmental burdens over a significantly larger electricity output. Improvements in degradation rates and higher module efficiencies further increase lifetime energy generation, resulting in lower impacts per functional unit of electricity.

Material resource depletion

Within the material resource depletion category, Scenario S1 shows the highest impacts at approximately 9.0×10^{-6} kg Sb-eq./kWh. Scenario S2 decreases to about 6.9×10^{-6} kg Sb-eq./kWh, representing an approximate 23 percent reduction, while Scenario S3 further reduces impacts to around 6.6×10^{-6} kg Sb-eq./kWh, corresponding to an overall reduction of about 27 percent compared to Scenario S1. Across all scenarios, the dominant contribution arises from solar cell manufacturing, accounting for approximately 68 percent of total impacts, primarily due to silver use in metallization paste, which alone contributes nearly 65 percent. Inverter production contributes around 32 percent of total impacts, largely driven by gold use in integrated circuit boards, which accounts for nearly 29 percent of the overall impacts.

5.3.2 Degradation rate sensitivity analysis

The breakeven analysis presented in Figure 4.1 evaluates the carbon footprint per kWh (g CO_2-eq/kWh) of three scenarios as a function of system lifetime. Scenario S1 represents the baseline configuration and is shown as a horizontal reference line at 36.19 g CO_2-eq/kWh. This value reflects the carbon intensity of the conventional system under standard assumptions. In this comparison framework, S1 serves as the benchmark against which the repowering strategies are assessed.

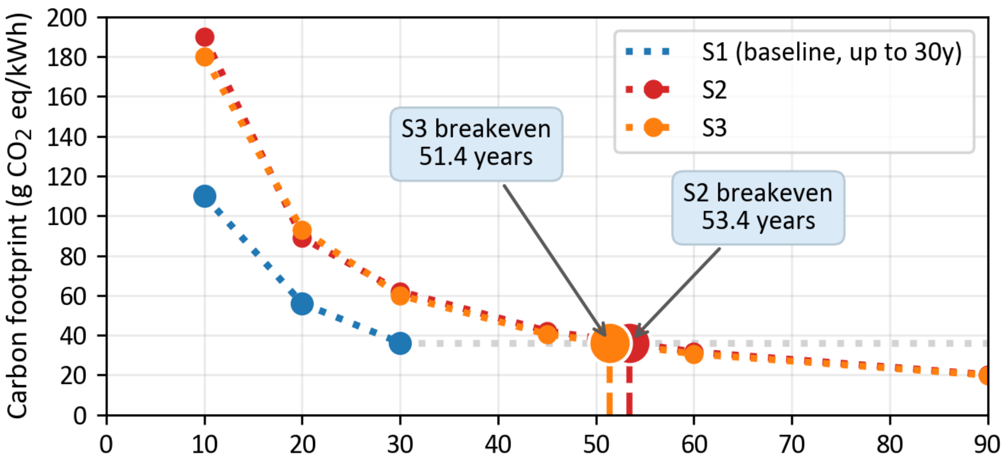


Figure 4.1 Breakeven analysis of carbon footprint (g CO_2-eq/kWh) as a function of system lifetime for the three SHJ photovoltaic configurations. Scenario S1 represents the baseline configuration and is shown as a constant reference line. Scenarios S2 and S3 represent repowering strategies with periodic cell replacement, with S3 incorporating higher-efficiency cells at each repowering cycle. The vertical dashed lines indicate the breakeven lifetimes at which the carbon footprint of the repowered scenarios equals that of the baseline configuration. The analysis illustrates the relationship between lifetime extension and impact per functional unit under the defined system boundary (cradle-to-grave).

In contrast, scenarios S2 and S3 exhibit a pronounced decrease in carbon footprint with increasing operational lifetime. This trend arises from the way impact per kWh is calculated, namely by dividing total life-cycle emissions by total lifetime electricity generation. Repowering introduces additional manufacturing burdens, primarily from the production of replacement solar cells. These processes are energy-intensive, particularly silicon wafer production, which significantly contributes to overall greenhouse gas emissions. At shorter lifetimes, the added manufacturing impacts from repowering are distributed over a relatively limited amount of electricity generation, resulting in higher carbon intensity values compared to the baseline. However, as lifetime increases, cumulative electricity production grows substantially while the embedded manufacturing emissions remain finite. Consequently, the carbon footprint per kWh decreases as the same environmental burden is amortized over a larger energy output.

The analysis identifies clear breakeven points for both repowering strategies. Scenario S3 reaches parity with the baseline at approximately 51.4 years, while S2 reaches breakeven at approximately 53.4 years. Below these lifetimes, repowering results in a higher carbon intensity than the conventional configuration, indicating that the additional manufacturing emissions outweigh the benefits of reuse and extended operation. Beyond these thresholds, the repowering strategies become environmentally advantageous, as the extended electricity generation compensates for the initial and replacement-related emissions. The existence of a breakeven lifetime demonstrates that repowering is not inherently beneficial; its sustainability depends critically on achieving sufficiently long operational durations.

The earlier breakeven point observed for S3 compared to S2 is attributable to performance improvements embedded in this scenario. S3 assumes enhanced technical characteristics, such as higher conversion efficiency and reduced degradation rates. These improvements increase total lifetime electricity generation relative to S2. Since carbon intensity is inversely proportional to cumulative energy production, the enhanced performance accelerates the reduction in g CO_2-eq/kWh and shifts the breakeven point to an earlier lifetime. This indicates that performance optimization plays a more decisive role in reducing carbon intensity than repowering alone.

At extended lifetimes between 60 and 90 years, both S2 and S3 show substantial reductions in carbon footprint relative to the baseline. The downward slope of the curves reflects the dominant influence of lifetime electricity generation on impact normalization. As operational duration increases, the relative contribution of manufacturing emissions diminishes in importance compared to total generated energy. This behaviour underscores the strong sensitivity of carbon intensity to lifetime assumptions in life cycle assessment studies of photovoltaic systems.

Overall, the breakeven analysis demonstrates that repowering strategies can reduce carbon intensity, but only under conditions of significant lifetime extension. If systems are decommissioned prematurely, the additional manufacturing emissions associated with replacement cells cannot be sufficiently amortized, and environmental benefits are not realized. Among the evaluated scenarios, S3 provides the most favourable long-term outcome due to its improved performance characteristics, achieving breakeven earlier and delivering greater reductions in carbon footprint at extended lifetimes. These findings highlight the importance of combining repowering strategies with technological performance enhancements and realistic lifetime extension in order to achieve meaningful carbon mitigation benefits.

4.3.3 Comparison with the literature

Life cycle assessment (LCA) literature on silicon heterojunction (SHJ) photovoltaics consistently reports climate change impacts in the range of 20–50 g CO_2-eq./kWh, depending primarily on system boundary definitions, electricity mix, module efficiency, degradation assumptions, balance-of-system (BoS) inclusion, and irradiation conditions.

Louwen et al. (2015) conducted a harmonized cradle-to-grave LCA of crystalline silicon photovoltaic systems, including SHJ configurations, using electricity generation (kWh AC) as the functional unit. Their system boundary included inverter and mounting structures, assuming European irradiation levels (~1000–1200 kWh/m²·year) and typical system lifetimes of 25–30 years. Reported greenhouse gas (GHG) emissions ranged from approximately 30–45 g CO_2-eq./kWh for contemporary SHJ systems and 20–30 g CO_2-eq./kWh for prospective high-efficiency configurations under improved manufacturing electricity mixes. Scenario S1 in the present study (36.19 g CO_2-eq./kWh) lies within this contemporary SHJ range and applies a cradle-to-grave boundary including inverter and mounting systems under comparable irradiation assumptions. Scenarios S2 (20.17 g CO_2-eq./kWh) and S3 (19.85 g CO_2-eq./kWh) align with the lower bound of prospective SHJ values; however, the reduction in this study is primarily driven by extended lifetime (90 years) and component reuse, rather than manufacturing decarbonization alone (Louwen, Sark, Schropp, Turkenburg, & Faaij, 2015).

Bhardwaj (2024) evaluated SHJ modules manufactured in the Netherlands using both cradle-to-gate and cradle-to-grave system boundaries. The cradle-to-grave assessment included inverter replacement and BoS components under average European irradiation conditions (~1000 kWh/m²·year), assuming 30-year operational lifetime. Reported impacts ranged between 25–40 g CO_2-eq./kWh depending on silver content and degradation rate. Scenario S1 (36 g CO_2-eq./kWh) is directly comparable in boundary definition and irradiation context. The lower values observed in Scenarios S2 and S3 arise from modeling structural component reuse (glass, frames, encapsulants) across multiple 30-year cycles—an approach not explicitly considered in Bhardwaj (2024), where full module replacement was assumed (Bhardwaj, 2024).

Frischknecht et al. (2020), within the IEA PVPS Task 12 framework, reported cradle-to-grave GHG emissions for crystalline silicon PV systems between 20–40 g CO_2-eq./kWh depending on production region, grid intensity, and installation type (ground-mounted systems with European irradiation levels). Their system boundary includes inverter and major BoS components, which ensures consistency with the present study’s modeling approach. The dominance of wafer production, silver metallization, and glass manufacturing identified in IEA PVPS Task 12 aligns structurally with the contribution analysis presented here (Frischknecht, Stolz, Krebs, Scholten, & Sinha, 2020).

A comparison with recent literature further supports the robustness of the present results. The study published in *Solar Energy Materials & Solar Cells* (2021) reports cradle-to-grave climate change impacts for crystalline silicon PV systems typically in the range of approximately 25–45 g CO_2-eq./kWh, including inverter and mounting components under conventional 25–30 year lifetime assumptions. Scenario S1 (≈36 g CO_2-eq./kWh) lies well within this interval, indicating methodological consistency. That study similarly identifies single-crystalline wafer production as the dominant contributor to both greenhouse gas emissions and non-renewable energy demand due to high electricity consumption, with additional significant contributions from silver metallization, glass production, aluminium mounting structures, and inverter electronics—patterns that align closely with the contribution analysis presented here. The lower impacts observed in Scenarios S2 and S3 (≈19–21 g CO_2-eq./kWh and ≈0.31–0.32 MJ/kWh) arise primarily from extended lifetime and structural component reuse rather than reduced per-module manufacturing intensity, distinguishing the present repowering-based modeling approach from conventional single-lifetime assessments in the literature (Müller, et al., 2021).

It should be noted that the primary methodological distinction between the present study and the referenced literature lies in lifetime assumptions. Most studies assume 25–30 years of operation with single module replacement at end-of-life. In contrast, the present study evaluates extended 90-year system lifetime with periodic cell repowering while retaining structural components. Consequently, the lower impacts observed in S2 and S3 result from amortizing manufacturing burdens over substantially higher cumulative electricity generation. When lifetime is reduced to 45–60 years in the sensitivity analysis, impact values converge toward literature ranges, reinforcing the strong dependence of LCA results on service-life modeling.

Finally, while explicit repowering assessments for SHJ modules are limited in the literature, LCA methodology consistently demonstrates that environmental impacts per kWh decrease when manufacturing burdens are distributed over larger lifetime electricity output. The breakeven analysis conducted in this study confirms that repowering becomes environmentally advantageous when operational lifetime exceeds approximately 50 years, reinforcing the principle of impact amortization through extended service life and component reuse.

5 DISCUSSION AND CONCLUSIONS

5.1 Discussion

This study evaluates the environmental performance of three silicon heterojunction (SHJ) photovoltaic system configurations under current industrial and electricity conditions. The comparison between a conventional module (S1), a repowered module with cell replacement (S2), and a repowered module integrating higher-efficiency cells (S3) demonstrates that repowering strategies can substantially reduce environmental impacts per unit of electricity generated, provided that system lifetime and performance improvements compensate for additional manufacturing burdens.

Across most impact categories, Scenario S1 consistently exhibits the highest impacts per kWh after the year 52. This is particularly evident in climate change, acidification, non-renewable energy use, ionizing radiation, and several toxicity-related categories. The primary reason for this trend is the concentration of environmental burdens within the initial manufacturing phase, especially during single-crystalline silicon wafer production and cell processing. Wafer production is highly electricity-intensive due to silicon purification and Czochralski crystal growth. Beyond climate change, similar structural patterns are observed in acidification, non-renewable energy use, and ionizing radiation, where electricity-intensive processes dominate. In toxicity and eutrophication categories, cell manufacturing again plays a central role, particularly due to metallization paste (linked to silver mining), wastewater treatment from texturing processes, and upstream metal refining. In several categories, inverter production and mounting systems contribute significantly, especially where aluminum, gold, or integrated circuit boards are involved. Water use is overwhelmingly driven by Czochralski silicon production, accounting for approximately 96 percent of total impacts. Material resource depletion is primarily influenced by silver use in metallization paste and gold in integrated circuits.

Scenarios S2 and S3 demonstrate clear reductions in impacts per kWh when evaluated over a 90-year lifetime. Although repowering introduces additional cell manufacturing impacts every 30 years, these are offset by extended operational lifetime, sustained electricity generation, and improved degradation performance. Scenario S3 achieves slightly lower impacts than S2 due to the integration of higher-efficiency cells during repowering cycles, which increases lifetime electricity yield and reduces impacts per functional unit. The degradation analysis supports this outcome: efficiency resets at repowering intervals mitigate cumulative performance loss, thereby maintaining higher average system output over time.

However, the sensitivity analysis reveals that these benefits are highly dependent on total system lifetime. When the total lifetime is reduced from 90 years to 60 years, and further to 45 years, while maintaining two replacement cycles, the environmental advantage of repowering diminishes significantly. At 60 years, S2 and S3 still outperform S1, but the margin narrows considerably. At 45 years, both S2 and S3 exceed the carbon footprint of S1. This demonstrates the existence of a break-even lifetime threshold. If the operational period is insufficient to distribute the additional manufacturing impacts of replacement cells over adequate electricity production, repowering becomes environmentally disadvantageous. This finding highlights that circular interventions are not inherently beneficial; their performance depends critically on system longevity and operational stability.

It is important to note that end-of-life recycling is excluded from the system boundary due to insufficient reliable data for large-scale SHJ module recycling under current conditions. As a result, no recycling credits or avoided burden allocations are applied. This exclusion ensures methodological transparency but also implies that potential circular benefits from future recycling technologies are not captured. Consequently, the environmental performance of repowering strategies is evaluated solely based on extended use-phase electricity generation rather than material recovery.

5.2 Conclusions

This study assessed the environmental performance of three SHJ photovoltaic system configurations under current European conditions. The results show that repowering strategies (S2 and S3) can significantly reduce impacts per unit of electricity generated when evaluated over extended lifetimes of 90 years. Scenario S3, integrating higher-efficiency cells, consistently achieves the lowest impacts across most categories due to improved lifetime energy yield.

The analysis confirms that single-crystalline silicon wafer production is the dominant contributor across multiple impact categories, particularly climate change, ionizing radiation, non-renewable energy use, and water consumption. Additional contributions arise from metallization paste, aluminum production, inverter manufacturing, and integrated circuit fabrication. Electricity consumption in energy-intensive processes remains the principal environmental driver.

The break-even analysis demonstrates that the environmental benefits of repowering are strongly dependent on total operational lifetime. While repowering reduces impacts at 90 and 60 years, it becomes environmentally unfavorable at 45 years. This indicates that lifetime extension and sustained performance are critical conditions for circular design strategies to deliver measurable environmental improvements.

End-of-life recycling was excluded due to a lack of robust data, and no recycling credits were applied. Therefore, the results reflect cradle-to-use impacts and do not account for potential future material recovery benefits. This boundary choice ensures transparency but also indicates that further research is required to evaluate the full circular potential of advanced SHJ modules.

In conclusion, repowering SHJ photovoltaic systems offers substantial environmental advantages when long-term operation is guaranteed and degradation is effectively managed. However, the environmental superiority of such strategies is contingent upon system longevity, stable performance, and the carbon intensity of upstream wafer production. Future decarbonization of silicon manufacturing and improved end-of-life data availability will be decisive in further enhancing the sustainability of SHJ photovoltaic technologies.

The environmental performance of the repowering scenarios assessed in this study is based on current conditions, and two prospective developments could further reduce the breakeven lifetime identified for Scenario S3. First, while end-of-life recycling was excluded from the present system boundary due to insufficient infrastructure data, the 30-year operational cycles modeled in S2 and S3 align with the timeframe over which dedicated recycling pathways for SHJ modules are likely to mature. The European FRELP (Full Recovery End-of-Life Photovoltaic) process has demonstrated silicon recovery rates of 95% from crystalline silicon PV panels through mechanical and chemical treatments, while the ROSI (Return of Silicon) process employs thermal and chemical separation methods to recover ultra-pure silicon suitable for reintegration into solar and semiconductor manufacturing. If future recycling infrastructure enables silicon recovery from dismantled cells at these demonstrated efficiency levels — extracting and reprocessing the silicon material with lower environmental burden than virgin Czochralski silicon production — then the manufacturing impact of replacement cells in the repower kit would be substantially reduced. Since single-crystalline wafer production currently dominates the carbon footprint across all scenarios, reducing this burden through silicon material recovery would lower the cumulative embodied emissions of S3, shifting the breakeven point to an earlier lifetime than the approximately 52 years identified here. Second, the present study models upstream electricity consumption using a 2020 European electricity mix. Prospective scenarios incorporating a progressively decarbonized grid — consistent with European energy transition trajectories over the coming decades — would reduce the climate intensity of energy-intensive processes such as single-crystalline wafer production and cell processing. A greener electricity mix would lower absolute emissions for both the initial manufacturing phase and each repowering cycle, further improving scenarios those with additional manufacturing events, such as S2 and S3.

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7 CONTRIBUTION TO THE TKI URBAN ENERGY INNOVATION PROGRAM

While the low prices of Chinese manufactured PV panels are welcomed to accelerate the deployment of PV on Europe's lands and roofs, it creates a deeply precarious situation for European solar PV manufacturers, pushing back the European PV reshoring plan targets. About 95% of the upstream value chain (polysilicon, ingot, wafers and cells productions) is located in China, making Europe's energy transition strategy completely dependent on a unique player in a complicated geopolitical scenario. Furthermore, the elimination of export discounts recently announced, in combination with increasing cost of silicon ingots and silver pastes is likely to increase the cost of silicon PV modules by 20-30% in the short term.

Pangea is firmly anchored with the roadmap 'routekaart circulaire zonnestroom systemen & weerbare sector'. PV power systems are essential for the energy transition, but they also use substantial amounts of raw materials and critical materials. The roadmap is in line with national circularity and raw materials strategies, to propose a jointly supported plan for circular PV systems and to contribute to a resilient Dutch manufacturing industry. This offers opportunities for circular processing in the Netherlands. With the National Circular Economy Program (NPCE), the Netherlands is aiming for a fully circular economy by 2050. On a global level this will need to be scaled up significantly in the coming years in order to have sufficient raw materials to continue producing the necessary PV power systems which will most likely have an effect on the energy transition within the EU.

Building a European manufacturing industry for PV panels and base materials can play an important role in Europe's strategic autonomy. This is a long-term and large-scale process full of challenges, but it is essential to promote circular processing of PV panels and materials in the Netherlands and the EU. Material reuse is a key element to close the loop, by rebuilding PV panels with material from end of life panels. Exchange of the solar cells with higher efficiency upgrades subscribes to positive LCA aspect that are described in WP4 of the demonstrated technology. Lower CO_2 emissions, fewer raw materials and sustainable use of products with a long technical lifespan within the reuse phase is promoted.

The project intends to return raw materials to the same production chains over time. For the short term release encapsulant enables access to the constituent materials and allow for further downstream recycling of the low iron glass sheet, solar cell contacting silver and finally the silicon. The project supports a healthy share of European and Dutch reuse material assisting in reducing dependence on a single country in pursuit of strategic autonomy.

Employment and environmental aspects
Reuse of recyclates offers direct savings in energy and that translates directly into the TNO patented and manufactured encapsulant of TCC adding track for employment within the energy transition. The ambition of The Compound Company as a production company is to become the key provider of release encapsulant within the next 10 years. This will improve Design for recycling of PV panels as currently tested by TNO and PV module manufacturer Q-cells.

Reducing Dutch economy dependence
This project contributes (indirectly) to reducing Dutch economic dependence on scarce material as silver and in the critical material silicon. Existing PV panels produced in China are a burden when it comes to disassembly at EoL. However, the low iron glass and metal raw materials are of value in case of reuse in a proper form.

Potential negative impacts on ecology and sustainability
Regarding the ecological side effects of the project, the former and present partners aimed for minimal negative impacts on ecology and fully support sustainability. If successfully implemented

at The Compound company the project outcomes will definitely have a substantial positive impact on ecology and sustainability, such as a reduced carbon footprint.

Primary raw material aspects

Extracting minerals from less accessible locations will eventually increase costs and energy, and scenarios predict that by 2050 up to 40% of the world's energy consumption will be used for this purpose. This makes reuse in circular processes a necessity. Additionally, it has become apparent that many raw material mining practices are not in line with EU Conflict Minerals Regulation. This mandatory due diligence of various minerals undergo import screening to safeguard higher ESG standards such as human rights, against forced labour, and conflict financing. Recycling and reuse are the better alternative to the extraction of raw materials.

Specific link to the MMIP2 program

The main aim of MMIP2 is to enable broadly applicable innovations in technology to allow for cost reduction and integral sustainability. The main focus of project Pangea Circular is on further improvement of novel materials, processes and remanufacturing allowing full circularity and re-use potential of PV panel components. The project thus mainly fits in program line 1a: 'Zonnestroomtechnologieën'. Long lifetime and low production costs are also important focus points of the program. The project will demonstrate reusing technologies and adds knowledge to LCA data, taking into account the environmental impact, resource efficiency and circularity potential. Inherently waste stream materials are used and toxic materials mitigation is applied. Material re-use will lead to identical or higher profit margin owing to a circular product enabling reduction in production costs and CO_2 emissions. The results of this project will create impact also for program line 2b as it calls for future applications on infrastructure like solar parks or noise barriers. Reliability, safety, and integrability aspects of reassembled solar panels are part of the Pangea Circular project.

8 CONTRIBUTION TO KNOWLEDGE DISSEMINATION

Extended session regarding release encapsulant at Sun Chain conference, November 5th 2025

9 TABLE LISTING KPI'S

KPI	Description
TRL at the end of the project Main categorie	Industrial @TCC Experimental @TNO
TRL at the end of the project Detail categorie	Release encapsulant 7
Project succes	The project has been completed in accordance with the original scope. All milestones have been achieved
Follow-up	Prototype development with Q-Cells within EU Horizon project 'Shine'. TKI toeslag proposal Separation. • Market launch
Number of peer-reviewed publications achieved	-
Number of peer-reviewed publications pending	-
Number of non-peer-reviewed publications achieved	-
Number of patent applications filed	TNO Releasable encapsulating layers for encapsulated objects Nr EP25181141.0.
Number of licences granted	Non
Number of prototypes	-
Number of demonstrators	-
Number of spin-offs/spin-outs	-
Number of new or improved products/processes/services introduced	-

KPI	Description
Impact **(explained in the final report)**	The novel development of the fast release encapsulant impacted PV industry with an unique product developed in the Netherlands. TNO and PV module producer Q-cells are going to apply the release encapsulant on the Q-cells production pilot-line within an EU Horizon project. Several joint EU Horizon projects with PV industry are underway or in the launching phase to roll out release encapsulant and support reuse. Pangea yielded very good results regarding reuse options and truly circular production schemes. The LCA study assessed the environmental performance of three SHJ photovoltaic system configurations under current European conditions. Results showed that repowering enabled by release encapsulant can significantly reduce impacts per unit of electricity generated when evaluated over extended lifetimes of 90 years (reuse of PV module materials and repowering with new solar cells). Integrating higher-efficiency cells, consistently achieves the lowest impacts across most categories due to improved lifetime energy yield. Project partner TCC Netherlands, Austrian company PCCL and the Scandinavian encapsulant manufacturer Norner believe that a unique product has been developed that will promote and support the European energy transition.