PRODUCT LIFE EXTENSION STRATEGIES FOR PV IN THE NETHERLANDS: THEORY AND PRACTICE

Thesis Research Project
Youri Haak
Delft University of Technology
Leiden University

Supervisors
David Peck — TU Delft – Architecture
Benjamin Sprecher — TU Delft – Industrial Design Engineering

FOREWORD

With the rapidly expanding deployment of renewable energy technologies, it seemed that now was a good time to evaluate some of challenges that lay ahead. It took a while to pinpoint the exact research gap to explore. There were simply too many interesting topics that combined sustainability, renewables, criticality, and circularity. Looking back, I am glad to have taken this path that led to many interesting insights, conversations and opportunities for improvements going forward. I have learned a lot along the way, beyond the skills needed for research, which I hope to apply in the future.

This thesis would not have been possible without the help others. I would like to express my gratitude and appreciation to my supervisors, starting with David, for his unwavering support, insights, and for our many interesting conversations and discussions. And to Benjamin for his supervision and feedback that helped accelerate this thesis project in the final stages.

Many thanks to all those I have been in contact with over the course of this study, who provided their insights and expertise. You have been an essential part of the process and your contributions were indispensable to its finalisation.

Special thanks to all my close friends for their feedback and support, and for being there for me when times were tough. And to the study group for helping me stay motivated, you know who you are. Lastly, to my family, for continuing to believe in my ability to successfully finishing my masters and for providing the necessary distractions that kept me grounded.

ABSTRACT

The EU has set out to reduce negative impacts from electricity generation on the environment, human health and towards our dependence on fossil fuels. As the fastest growing renewable source of electricity, photovoltaics plays an important role in the energy transition. The manufacturing of photovoltaic modules requires materials classified as critical, making them prone to supply disruptions. Although these materials are essential to the EU economy, they are not sufficiently recovered at the end of a photovoltaic module's life. An alternative intermediate solution could be to extend the lifespan of existing modules, to slow down demand for these materials in the future.

The aim of this study was to analyse the theoretical options and practical examples of product life extension strategies for photovoltaics. The R-Ladder was used as a guiding framework, which provided examples of life extension strategies. These include Reuse, Repair, Refurbishment, Remanufacture and Repurpose. Aspects for each of these strategies were analysed to find potential benefits and challenges related to four aspects: economics, environment, energy, and materials.

The approach of this study includes a literature review to identify the life extension strategies discussed specifically for photovoltaics in the context of the circular economy. This was followed by a multi-case study on practical applications of Reuse, Repair and Repurposing of photovoltaic modules. Findings from literature and the case study were further supplemented with the insights from six experts. These experts had diverse backgrounds in research, manufacturing, and procurement to offer a variety of insights and perspectives on life extension strategies for photovoltaics. Finally, two scenarios were created for possible life extension pathways for used photovoltaic modules to illustrate the potential impacts compared to a commonplace premature replacement scenario.

Economics and module performance are key factors in decision-making and acquisition of a photovoltaic system. Reuse offers a compelling alternative to current recycling capabilities but offers no sufficient business case. Repair may extend a module's lifespan to continue the generation of renewable electricity but is only possible in cases of minor damage for which replacement parts are available. Refurbishment could restore more severe damage but is limited by economies of scale and the technical difficulties resulting from current photovoltaic module design. Remanufacturing has the potential to restore a solar cell's original performance or even upgrade it using newer processing methods but suffers from the same design limitations as Refurbishment. Repurposing used modules can offer a pathway to extract the remaining capacity if it is implemented in a context where generation density is of no concern. Combined, these strategies could buy time to address the resource challenges amplified by the energy transition.

Keywords

Circular Economy
Critical Raw Materials
Energy Transition
Photovoltaics
Product Life Extension

TABLE OF CONTENTS

ABBREVIATIONS

BOM	Bill of Materials
CdTe	Cadmium Telluride
CE	Circular Economy
CIGS	Copper Indium Gallium Selenide
CRM	Critical Raw Material
c-Si	Crystalline Silicon
DSSC	Dye-Sensitised Solar Cells
EoL	End-of-Life
EU	European Union
EVA	Ethylene Vinyl Acetate
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
NICE	New Industrial Cell Encapsulation
OEM	Original Equipment Manufacturer
PFAS	Perfluoroalkyl and Polyfluoroalkyl Substances
PID	Potential-Induced Degradation
PLE	Product Life Extension
PoM	Put on Market
PV	Photovoltaic
QR	Quick Response
R&D	Research & Development
RFID	Radio-Frequency Identification
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt hour
Wp	Watt peak

INTRODUCTION

Since the industrial revolution the use of electricity has increased while the sources used to generate this electricity continue to largely rely on burning fossil fuels (IEA, 2021; IPCC, 2014). These fuels produce emissions harmful to, among others, our environment and health. A transition from fossil resources towards renewable resources aims to address some of these major concerns. However, this transition can create new challenges including materials use, supply and demand, and waste.

Transitions of Dependencies

The European Union (EU) has ambitious plans to reduce their dependence on fossil fuels. These include (1) a reduction of greenhouse gas (GHG) emissions of at least 55% by 2030, and (2) a target for 45% renewables in the EU energy mix by that same year (European Commission, 2022). Similarly, the Dutch government has set a goal of at least 27% renewable energy by 2030 (Ministerie van Algemene Zaken, 2022). Two transitions play a key role here; the energy transition and the digital transition (Muench et al., 2022). However, the technologies needed to facilitate these transitions require materials, which changes our dependence on fossil fuel resources to a dependence on materials (Gielen et al., 2019).

This materials demand, amplified by the push towards renewables, is expected to take up a large portion of overall materials demand in the future. For several key resources, such as aluminium, copper and silicon metal, the proportion required for the energy transition by 2040 could reach 30%, 35% and 50% of the total current consumption in the EU respectively (Gregoir & Van Acker, 2022) (Figure 1).

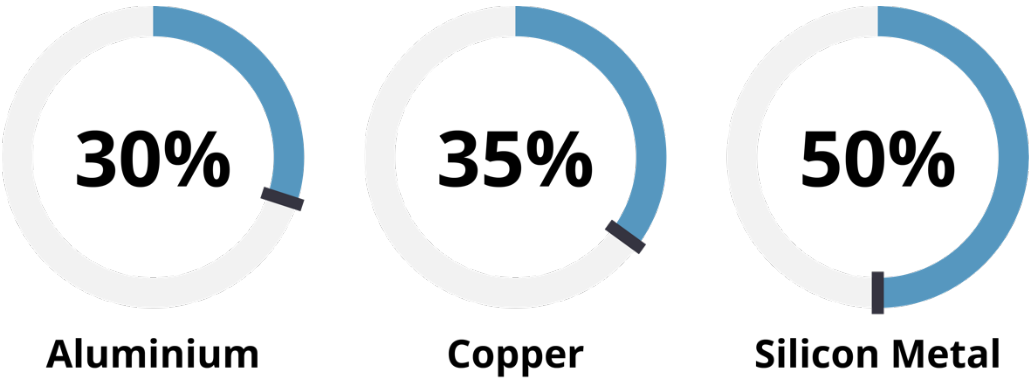

Figure 1: Proportion of material need for the energy transition by 2040 compared to current total consumption in the EU

The increase in demand is potentially problematic because these materials are also used in other important sectors. Aluminium is frequently used in construction, electrical appliances and consumer goods. Copper is used in infrastructure, industry and transport. Finally, silicon metal is used in chemicals and alloying applications for the aluminium industry. Several technologies will play an important role in the energy transition, such as solar panels and wind turbines. However, it is important to examine the materials needed to produce these technologies, especially the ones that have been labelled as critical.

Critical Raw Materials

Raw materials are labelled 'critical' by the European Commission depending on both their economic importance and the potential for disruptions to their supply (European Commission, 2017, 2020). These Critical Raw Materials (CRM) are used in various sectors, increasingly so in electricity generation technologies for our energy transition. The supply risk is amplified by the fact that many of these materials are typically sources from outside the EU region (Blagoeva & Pavel, 2017; European Commission, 2017, 2020; IEA, 2022; Schoer et al., 2012) (Figure 2). Production of these materials is more geographically concentrated than for oil and gas resources, which gives those countries more leverage over their supply (IEA, 2020; USGS, 2021). This distribution may affect EU members' ability to successfully transition to renewables.

Figure 2: Geographic distribution of the share of several critical raw materials key to the EU energy transition

Several of these CRMs are commonly used in renewable energy technologies such as photovoltaics (PV). These materials include, among others, silicon metal, gallium, indium and antimony (Motta et al., 2016; Oteng et al., 2021; Smith & Bogust, 2018; Tao & Yu, 2015). Besides being labelled as critical, these materials are essential to the functioning and performance of current PV technologies.

Photovoltaics

PV, as part of the energy transition, is one of the key drivers for CRM demand (Gielen, 2021). The main materials demand for the most commonly used PV technology is from copper and silicon metal, the latter being listed as critical (IEA, 2022). Currently, PV is the fastest growing renewable energy source in the EU, partly caused by relative cost (Eurostat, 2022; Hof et al., 2022; Theelen et al., 2021). Over the last years, the price of PV has decreased, while its efficiency has only increased (Benda & Černá, 2020; Fraunhofer ISE, 2021; IRENA, 2019b). This increase in efficiency can be seen across three common PV technologies; crystalline-silicon (c-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) (Figure 3). The demand for PV and its subsequent materials is therefore only expected to grow.

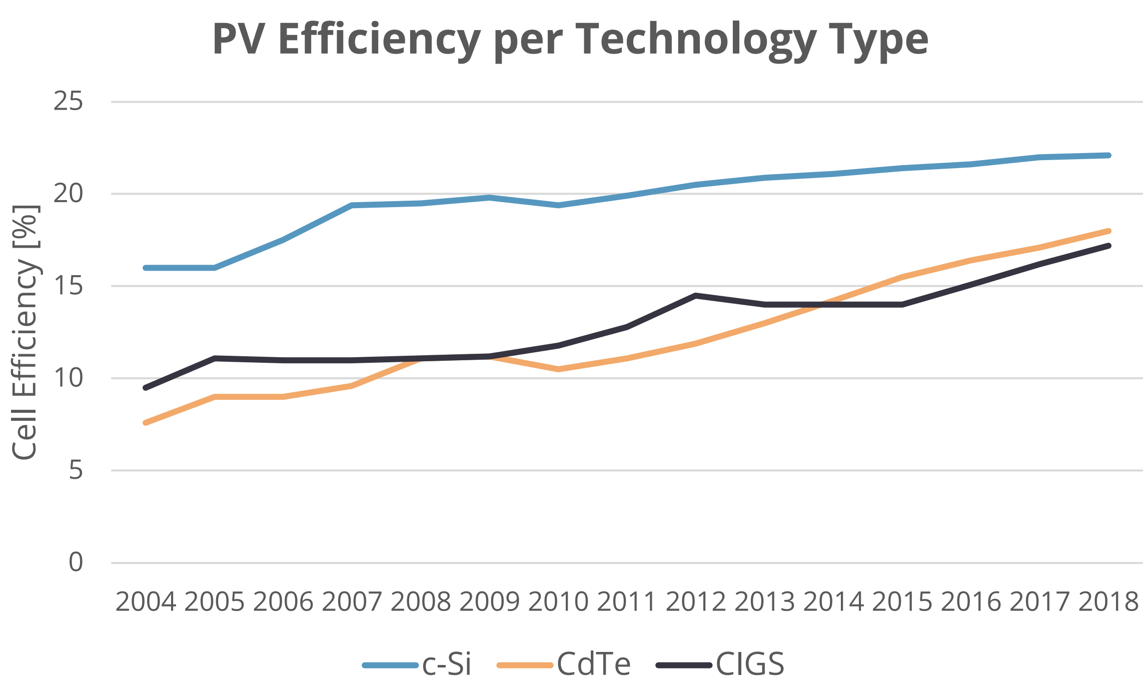

Figure 3: PV efficiency development over time, for three common technologies in use, adapted from Benda & Černá (2020), Fraunhofer ISE (2021) & IRENA (2019b)

This increase in the amount of PV installed can also be observed in the Netherlands. Over the last decade, the installed capacity has grown nearly exponentially year over year (CBS, 2022) (Figure 4).

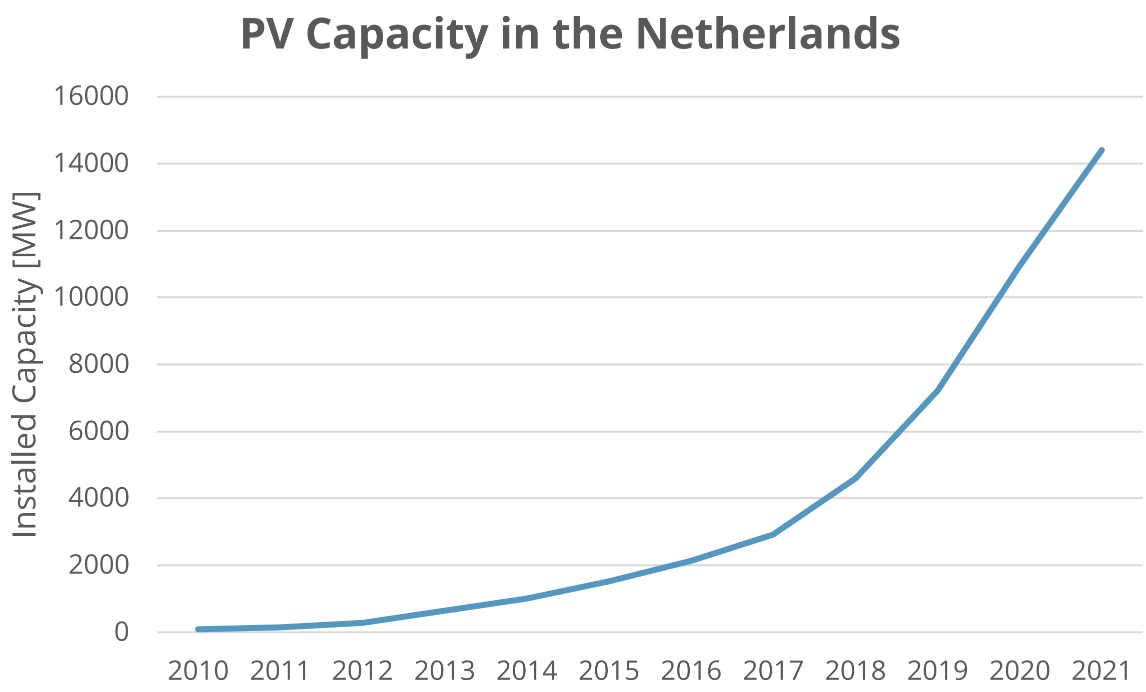

Figure 4: Growth of installed PV capacity in the Netherlands.

Main Types of PV

There are two main technology types of PV in current use. These differ in, among others, their construction and materials used. The first group of crystalline-silicon (c-Si) modules are most common with a market share of ± 95% (Fraunhofer ISE, 2021). These are also known as first-generation PV and are expected to remain the dominant PV technology by 2040. This is partly due to their efficiency and to silicon's relative abundance globally (Charles et al., 2017; Chowdhury et al., 2020; IEA, 2022; Sharma & Goyal, 2020; Smith & Bogust, 2018; Wilson et al., 2020).

The general structure of c-Si modules is characterised by the silicon solar cells, sandwiched between two layers of Ethylene Vinyl Acetate (EVA) encapsulant, a glass sheet on the front, a plastic backsheet on the rear and an aluminium frame around the outer edge (Figure 5).

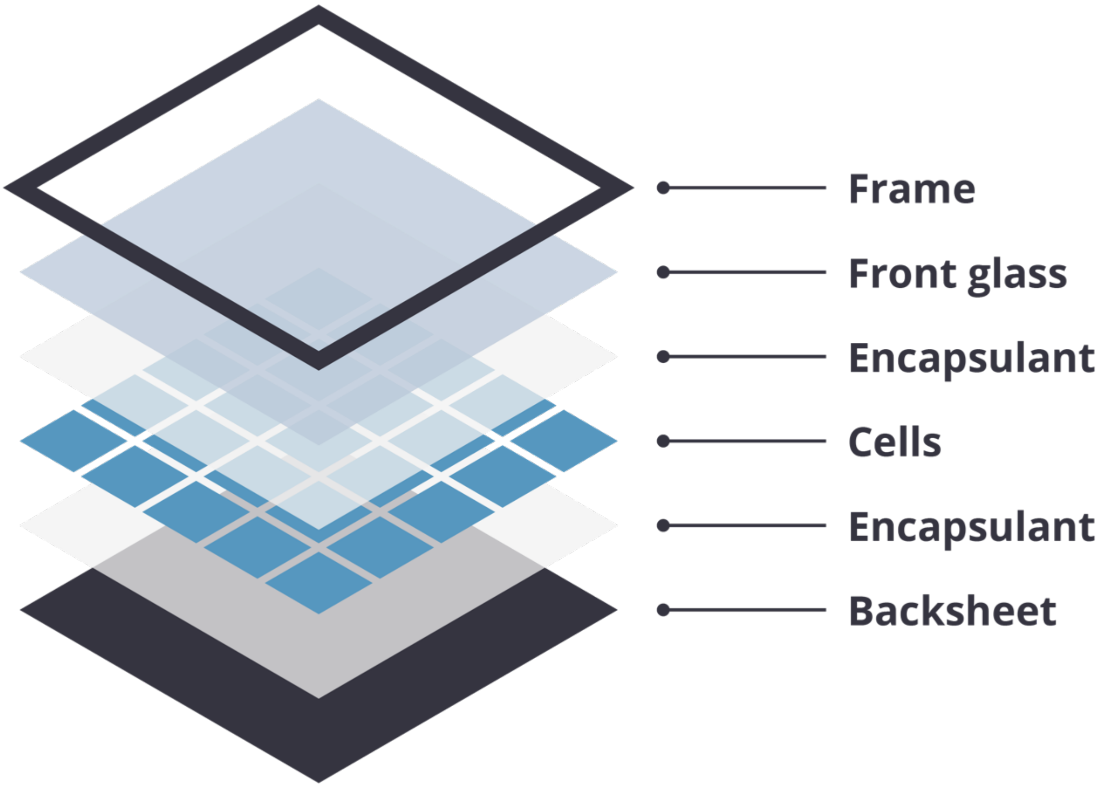

Figure 5: Layers in a typical c-Si PV module

The second technology type of PV are thin-film modules, which constitute the remainder of the PV market at ± 5% (Fraunhofer ISE, 2021). These are also known as second-generation PV. Their structure is characterised by thin layers of materials deposited on a substrate, usually glass or plastic film (Figure 6). Within thin-film PV, the most common technologies are Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). These technologies require less material compared to the c-Si modules, however, they rely more heavily on CRMs for their efficiency (Sharma & Goyal, 2020).

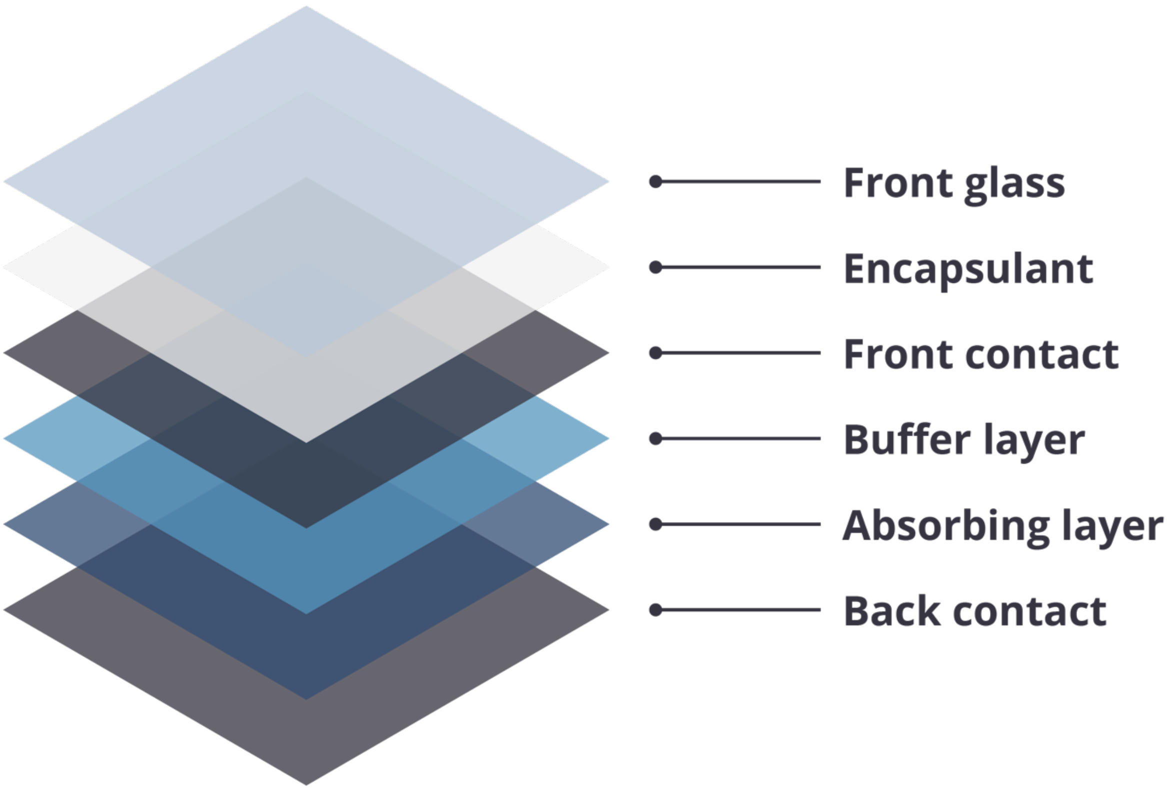

Figure 6: Layers in a typical thin-film module

Materials Breakdown

The layers within PV modules consist primarily of glass, aluminium and EVA encapsulant. The precious- and critical metals only make up a fraction of the overall mass. In c-Si PV, the silicon metal contributes to 4-5% of the overall module (IRENA, 2019a; Smith & Bogust, 2018) (Figure 7). In thin-films, the relative share of CRMs is even smaller compared to c-Si. This negatively affects the incentive to recover these materials at the end of a module's life.

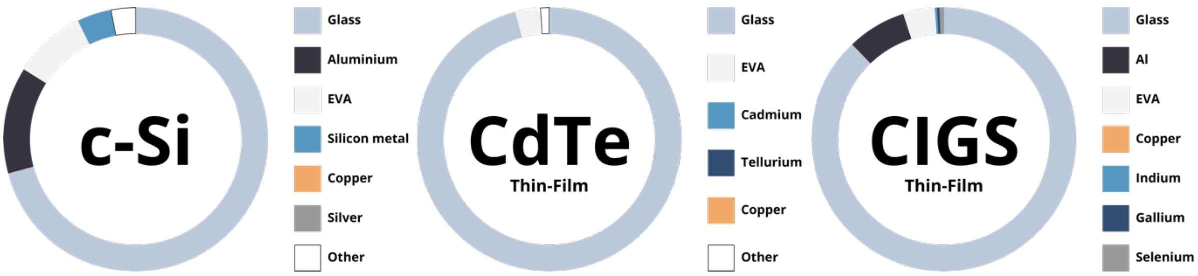

Figure 7: Material breakdown by % of mass for the three most commonly used PV technologies

Research & Development (R&D) efforts on both c-Si and thin-film PV have, and are continued to be made, to further reduce manufacturing costs while increasing electricity generation efficiency (Franco & Groesser, 2021; Oteng et al., 2021). This led to, among others, a decrease in material intensity for silicon metal and silver (Gregoir & Van Acker, 2022). However, less attention has been given towards the recovery of these materials at a product's End-of-Life (EoL).

EoL Recovery

PV modules may not be landfilled in the EU, as stated by the EU Waste Electrical and Electronic Equipment (WEEE) Directive (Walzberg et al., 2021). Under this legislation, 85% of PV must be recovered at EoL and 80% must be prepared for Reuse or recycling (EU, 2012). In the Netherlands, as of the 1st of March 2021, 'Stichting OPEN' is responsible for the financing of collection and processing of WEEE (Rijkswaterstaat, 2021). Data regarding the amount of PV that is Put on Market (PoM) and the amount collected for processing at EoL are gathered in a registry. This data suggests a discrepancy between installation and collection (Nationaal (W)EEE Register, 2018, 2019, 2020, 2021, 2022) (Table 1 & Figure 8).

Table 1: PV PoM and WEEE collection in the Netherlands

	2017	**2018**	**2019**	**2020**	**2021**
PoM [ton]	63270	96285	190476	237244	243707
Collected [ton]	20	131	124	771	493

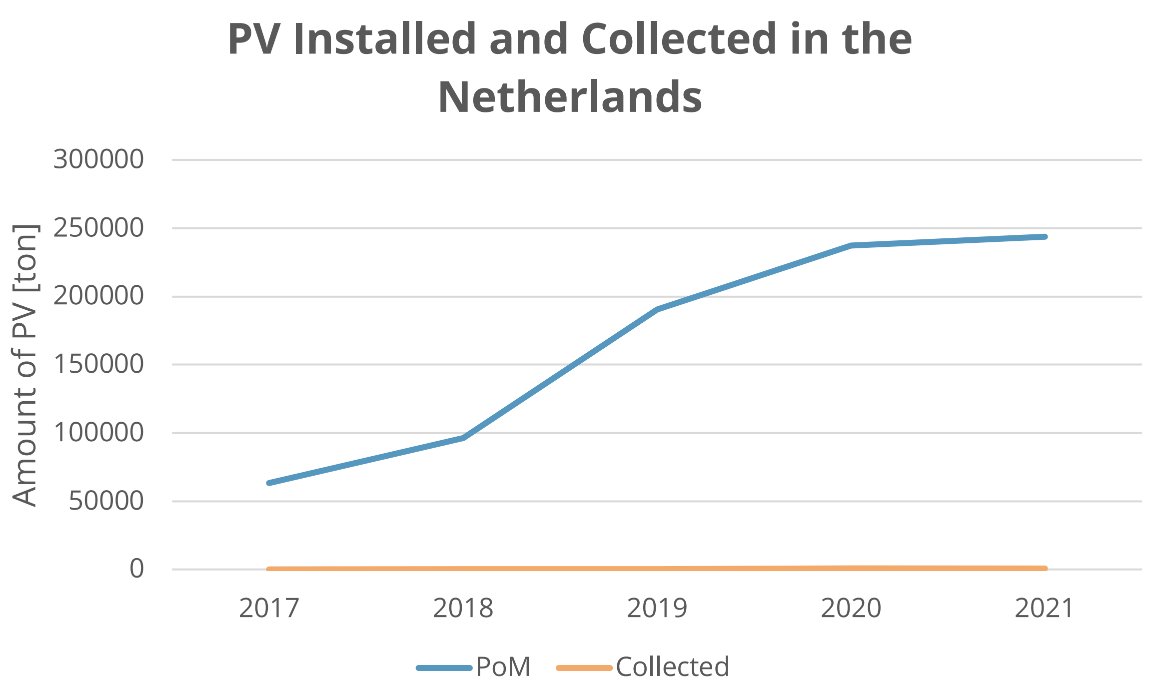

Figure 8: Difference between PV Put-on-Market and collected for recycling in the Netherlands

This discrepancy between the amount of PV installed to the amount collected can be partly attributed to the fact that PV has a lifespan of ± 25 years (Theelen et al., 2021). Therefore, the amount of PV available for collection and processing lags behind the installation-curve by roughly the same amount of time. It will take time for the collection and processing of EoL PV to reach the volumes that are installed at present.

EoL Processing

Currently, the most common processing method is destructive bulk recycling. This involves crushing or shredding the PV modules to reclaim part of the glass, aluminium and copper (Glatthaar et al., 2017). The effectiveness of this approach is uncertain, as often no real data regarding the recycling efficacy is available (Heath et al., 2020).

This lack of data on recycling efficacy is problematic, because in order to comply with EU legislation, 80% of the mass of a PV module must be reused or recycled (EC, 2012). Regarding the material composition of the most common PV technologies, the glass and aluminium frame, or in the case of thin-films just the glass, already meet this 80% mass requirement (Figure 9). The CRMs are often not recovered at a module's EoL, or at least not at a high enough purity to manufacture new PV modules. This low CRM recovery rate contributes to the challenge of meeting the materials demand for the energy transition (Gielen, 2021; Gregoir & Van Acker, 2022; IEA, 2022). The fact that PV modules are often replaced before they reach their technical EoL further amplifies the concerns for future balance of CRM supply and demand (Murakami et al., 2021). Therefore, alternatives to current means of recycling such as product life extension (PLE) may have a more immediate impact (Blagoeva & Pavel, 2017).

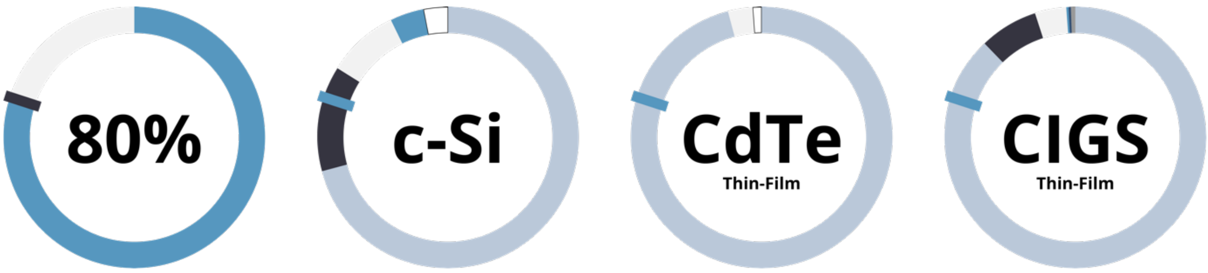

Figure 9: 80% recycling requirement compared to PV module material composition by mass% with an 80%-mark indication

Circular Economy

One theory for dealing more effectively with material resources is the Circular Economy (CE), where materials are cycled in (closed) loops over multiple product life cycles (Franco & Groesser, 2021; Ghisellini et al., 2016; Korhonen et al., 2018). The Ellen MacArthur Foundation presents three core principles to a CE: ‘eliminate waste & pollution’, ‘circulate products & materials’, and ‘regenerate nature’ (Ellen MacArthur Foundation, n.d.-b, n.d.-a, n.d.-c). Renewable energy technologies have the potential to contribute to the reduction of pollution. Depending on the way these technologies are implemented, specifically regarding circular approaches to the design, use and deployment of PV, it could promote waste reduction and effective circulation of products and materials. The R-Ladder framework provides specific strategies to reduce waste and increase product and component circularity.

R-Ladder

The R-Ladder framework presents several circular strategies. Each position on the ladder represents a way to maintain environmental-, material- and economic value, and the embedded energy within a product (Potting et al., 2018). The individual strategies can be grouped in three focus areas: (1) Design & Use Strategies, (2) Product & Component Life Extension Strategies and (3) End-of-Life Strategies (Figure 10). The first focus area concerns decisions made for product design and use-strategies. The second describes pathways to keep components and product in use for longer by extending their usable lifespan. The third focus concerns the EoL phase with the goal to recover the materials or energy embedded in the product.

A significant number of PV modules are already in use in the Netherlands, based on the installed capacity (CBS, 2021). Yet at the back-end, current recycling methods do not have the incentive to recover CRMs. Therefore, the focus of this study is on the second group of strategies to extend the lifespan of existing products. These include Reuse, Repair, Refurbishment, Remanufacturing and Repurposing. Reuse entails the exchange of a functioning product between two parties. Repair signifies the process of restoring functionality in a defective product. Refurbishment delves deeper than Repair and often includes (partial) disassembly of a product to replace components to restore functionality and/or the aesthetics of a product. Remanufacturing describes the process of fully disassembling a product and restoring it to the same level of quality as a new product or to upgrade it beyond the original specification. Repurposing a product outlines the use of the product in a new context or for a different purpose than the original use-context.

FOCUS	R STRATEGY	DESCRIPTION
Design & Use Strategies	R0 Refuse	Made redundant by cancelling function
	R1 Rethink	Use-intensification (product sharing, etc.)
	R2 Reduce	More efficient material use per product
Product & Component Life Extension Strategies	**R3 Reuse**	**Reuse of usable product by new user**
	R4 Repair	**Restore product functionality**
	R5 Refurbish	**Restore product functionality and aesthetics**
	R6 Remanufacture	**Restore product to new or better condition**
	R7 Repurpose	**Reuse of usable product or part in new context**
End-of-Life Strategies	R8 Recycle	Recover materials for use in new products
	R9 Recover	Incineration to recover energy from product

Figure 10: R-Ladder strategies, life extension strategies highlighted, adapted from Potting et al. (2018)

Key Issue Addressed

The two transitions aimed to achieve a more sustainable future drives material demand leading to a mismatch with supply in the coming years. Renewable energy technologies such as PV are key drivers of material demand, including CRMs. These materials are currently not recovered in sufficient quality and quantity at EoL. Using existing PV modules for longer may impact future demand for primary materials, including the demand for CRMs. However, PLE strategies are currently not widely applied in the field of PV technologies (Deng et al., 2021; Tsanakas et al., 2020). This study aims to identify which of these strategies may be relevant for the case of PV, what may be learned from practical applications of these strategies and how this could impact the resource challenges of the energy transition going forward.

METHODOLOGY

The aim of this research project was to identify and analyse theoretical examples and practical applications of PLE strategies for a growing PV market in the Netherlands. Life extension strategies for products and components, as described in the R-Ladder framework, were used to gain understanding about the interplay between PV and CE principles. Specifically, regarding their impact on materials demand, energy use, the environment and economic aspects of PV.

Research Questions

Main RQ:
How could product life extension strategies impact the way we expand PV deployment?

Sub-RQs:

1. What life extension strategies can currently be identified for PV?
2. How may practical applications of PV life extension strategies impact critical resource challenges?
3. How could the interplay between design for product life extension- and critical material supply-demand strategies affect the energy transition?

Research Flow Diagram

A mixed-methods approach was used to answer the research questions. These methods and the relation to these research questions were visualised in a Research Flow Diagram (Figure 11). Firstly, a literature review on the basis of the R-Ladder framework was used to identify relevant PLE strategies for PV as discussed in theory. Results from this review were used to answer sub-research question 1. Secondly, a case study was used to find and analyse practical examples of PLE strategies as implemented in practise. The literature findings were used to guide the search towards the most promising cases. For those cases, the context, impact and challenges related to the approach were explored to answer sub-research question 2. Thirdly, PV experts were interviewed to gain further understanding about the interplay between PLE strategies and the material challenges for the energy transition. The insights gained from these interviews were used to answer sub-research question 3. Fourthly, a conceptual model was created to provide guidance in the decision-making process towards potential PLE strategies for used PV modules. Feedback from PV experts during the interviews was used to refine this model. Lastly, based on the model and prior findings, two plausible PLE strategy implementation scenarios were created to visualise the potential impact in material and energy use, on the environment and towards economic aspects. All findings combined led to an answer to the main research question.

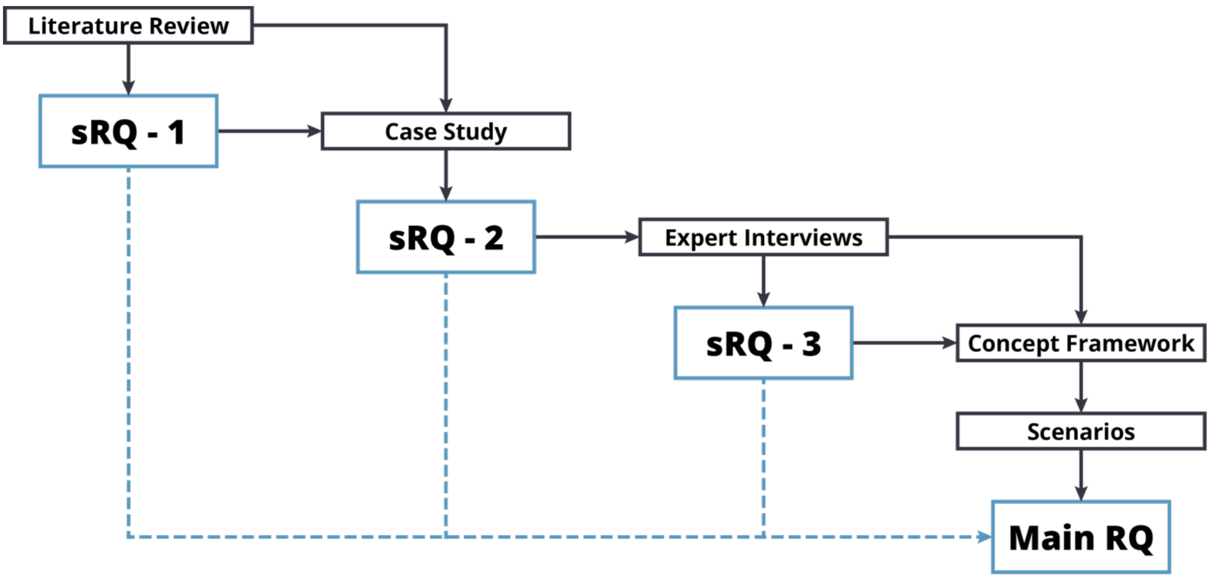

Figure 11: Research Flow Diagram

Literature Review

The literature review was chosen as the primary method to answer sub-research question 1; to identify current life extension strategies for PV.

Literature Search

Research on PLE strategies for PV was relatively limited when compared to research on EoL recycling strategies, as shown in an initial literature search (Table 2). Out of the R-Ladder PLE strategies, however, Reuse yielded most results. Although, these numbered less than a third compared to recycling in the same search.

Table 2: Initial search results for Life Extension Strategies compared to PV Recycling

Theme / R-Ladder Strategy	Query	Results
Life extension	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("lifespan" OR "lifetime" OR "life extension"))*	14
R3 Reuse	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("Reuse" OR "re-use"))*	23
R4 Repair	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("Repair"))*	4
R5 Refurbish	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("Refurbish" OR "Refurbishment"))*	4
R6 Remanufacture	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("Remanufacture" OR "remanufacturing"))*	5
R7 Repurpose	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("repurpose" OR "repurposing"))*	1
R8 EoL Recycling	*TITLE-ABS-KEY (("photovoltaic") AND ("circularity" OR "circular economy") AND ("recycle" OR "recycling"))*	76

The literature search was refined, searching the Scopus database for a query on life extension for PV in the context of a Circular Economy:

> *TITLE-ABS-KEY (("photovoltaic" OR "solar energy" OR "solar power") AND ("circularity" OR "circular economy") AND ("lifespan" OR "lifetime" OR "life extension"))*

The quantity of results from this search was deemed too limited to draw any meaningful conclusions about the various PLE strategies and was therefore expanded. New queries specific to each individual R-Ladder strategy were used to find additional literature results:

TITLE-ABS-KEY (("photovoltaic" OR "solar energy" OR "solar power") AND ("circularity" OR "circular economy") AND ("Reuse"))
TITLE-ABS-KEY (("photovoltaic" OR "solar energy" OR "solar power") AND ("circularity" OR "circular economy") AND ("Repair"))
TITLE-ABS-KEY (("photovoltaic" OR "solar energy" OR "solar power") AND ("circularity" OR "circular economy") AND ("Refurbish" OR "Refurbishing" OR "Refurbishment"))
TITLE-ABS-KEY (("photovoltaic" OR "solar energy" OR "solar power") AND ("circularity" OR "circular economy") AND ("Remanufacture" OR "remanufacturing"))

The new combination of search terms led to a combined 47 hits that were used for further analysis (Table 3). Strategy R7 (Repurpose) was not included in the literature review. The definition of Reuse in a different context was initially deemed not relevant for the use of PV, as its only purpose is to generate electricity. This strategy was however, included from the case study on, in further interviews and in the final concept model.

Table 3: Search results per combination of search terms for each relevant life extension strategy

R-Ladder	Term 1	Term 2	Term 3	Hits
R3 – R6	PV	CE	Life extension	16
R3 Reuse	PV	CE	Reuse	27
R4 Repair	PV	CE	Repair	5
R5 Refurb	PV	CE	Refurb	6
R6 Reman	PV	CE	Reman	7
Subtotal				61
Duplicates				14
Total				**47**

Literature Selection

Literature results were analysed based on their relevance towards identifying PLE strategies for PV. Literature clearly describing one or more PLE strategies were selected, whereas literature describing, e.g., PV recycling or PLE for other products such as electric vehicle batteries were excluded (Appendix A & B).

Some literature described multiple examples of PLE for PV that were previously not found in the literature searches. Those sources were included in the literature review for further analysis. In other situations, literature showed overlap between two or more PLE strategies. These sources were listed under both strategies and used to draw conclusions for both PLE strategies.

Literature Result Analysis

From the selected literature, all keywords were collected and presented in a 'word-cloud' and sorted by the frequency in which they were mentioned. This provided a quick overview of the main topics discussed in these papers, including topics not directly overlapping with the R-Ladder strategies.

Literature findings were grouped per PLE strategy. Within those strategies their specific impacts were presented under four main categories: economics, environment, energy and materials. These four categories are four out of the six major sectors involved in sustainable development as described by Ashby (2015): materials, energy, environment, economics, society and legislation. The last two, society and legislation, were not included as they were not part of the scope of this study. The literature findings were used to answer sub-research question 1 and formed a knowledge base for the case study.

Case Study

Case Study was chosen as the primary method to answer sub-research question 2; to find practical examples of life extension strategy implementations and their impact on critical resources. Specifically, a multi-case study was used to analyse three cases over three different strategies and to compare their respective approaches. The protocol used to structure the case study was adaption from Yin (2018) to fit the context of resource- and energy challenges for PV in a circular economy.

Case Study Overview

The case study builds upon the literature review to find and analyse the most commonly described PLE strategies from the R-Ladder framework. Since Reuse was described most often in literature, two Reuse-cases were included. Repair was included as part of one case where both Reuse and Repurpose were practised. This was simultaneously the point where the value of Repurpose was acknowledged, leading to its inclusion in the case study and throughout the rest of the study.

Protocol Questions

Yin (2018) describes five levels of questions to guide a case study. These include:

- Questions directly asked to the interviewee
- Questions that reflect the line of inquiry for each case
- Questions to do with patterns and findings across cases
- Questions for the entire study (beyond the case study)
- Normative questions about recommendations and conclusions

The level one questions were asked during the interviews and are part of the interview protocol (Appendix C). The level two questions, to help guide the study, include the following:

- Why was this PLE strategy chosen?
- What impact does the PLE strategy have on energy- and critical raw materials challenges?
- What are the primary benefits specific to this PLE strategy?
- What are the primary challenges specific to this PLE strategy?
- What is their view on current PV module design?

Level three questions were used to compare the three cases and included the following:

- To what context would this strategy befit?
- How does the chosen PLE strategy affect the module’s lifespan?
- What are direct impacts to the approach?
- What are indirect impacts to the approach?

Since the case study is part of the overall research project, level four and level five questions were not used specifically for the case study as they are already fulfilled by the overarching sub-research questions.

Tentative Outline for Result Presentation

Each case will follow a similar outline, starting with background information about the organisation itself. Followed by a description of their specific PLE implementation, and key insights related to the guiding questions (level two). The three cases are compared based on their impact on the four categories: economics, environment, energy and materials. And finally concluded by answering sub-research question 2.

Case Selection

Cases were selected based on being founded on one of the R-Ladder principal strategies or by having adopted a PLE strategy into their core business. Cases were searched via the list of members of Holland Solar, a trade association for Dutch solar energy companies (Holland Solar, n.d.). Only three were found to mention one of the PLE strategies and in all cases, this was Repair (Appendix D). However, none of them were included due to their description of Repair referring to maintenance or replacement of entire modules as a means to Repair a PV system, rather than Repair on an individual module.

The Fair Solar Network was identified as a network of organisations and individuals working towards circular and fair PV in the Netherlands. Their list of members was used to find two of the three cases, and was later on used to find further experts to interview (Fair Solar Netwerk, n.d.). A one-phase screen approach was used to select the cases, using the following criteria:

- Findability & data availability (e.g., they have a website with all the required basic information)
- Geographic location and origin (must be a Dutch organisation catering primarily to the Dutch market)
- R-Ladder relevance (they practise at least one PLE strategy for PV)

Selected Cases

ZonNext, member of the Fair Solar Network, was selected for Reuse due to their facilitating role in connecting parties offering second-life PV modules to parties searching for second-life PV modules (ZonNext, n.d.-c).

Marktplaats, was selected for Reuse as platform for buying and selling used PV modules amongst consumers (≥ *Vind Zonnepanelen | Zo Goed Als Nieuw in Zonnepanelen En Toebehoren Op Marktplaats*, n.d.).

Boldz, member of the Fair Solar Network, was selected for Repair and Repurpose. They develop an in-house Repair technique and integrate discarded PV modules into picnic tables for outdoor charging of mobile devices (Boldz, n.d.).

Data Collection Procedures

Each case started with data collected via desk research from publicly available web data, whitepapers and news articles. Two out of the three case study organisations were interviewed for further information on their specific implementation of one or two PLE strategies. The case of Boldz involved a semi-structured interview, which was recorded, transcribed and coded to find patterns into the relevant aspects to their business, including economics, environment, energy and materials. The case of ZonNext also involved a semi-structured interview, although in that case notes were taken during the interview process to capture the main discussion points specific to their approach. No interview was held with Marktplaats or any of the sellers or buyers on Marktplaats.

Case Study Data Analysis

Over a period of 5 weeks, all Marktplaats advertisements for used PV modules were analysed for the number of advertisements offering PV, number of modules offered, performance and age of the modules, and the reason why they were offered (Appendix E). These were filtered to remove duplicates and advertisements that did not provide all relevant information. Any advertisements from companies, offering new modules or requesting modules were excluded.

In the case of Boldz, desk research data was combined with the transcribed and coded results from a semi-structured interview (Appendix F). These were compared with the results from desk research and the interview with ZonNext (Appendix G). All cases were compared based on four aspects: economics, environment, energy and materials.

Expert Interviews

Semi-structured interviews were chosen as the primary method to answer sub-research question 3. Six experts were interviewed to verify the literature findings, gain further insight on the approaches found in the case study and to validate a concept framework to guide decision-making towards PLE strategies for PV at the end of its use cycle. Furthermore, they were used to discuss the limitations of current PV design and how it affects possibilities to perform one PLE strategy but not others. And

Participant Selection

Participants were selected based on their expertise in the field of PV. This included experts from TNO, the TU Delft Photovoltaic Materials and Devices Group, RIVM, RVO and a Dutch PV manufacturer. They were selected based on their work towards improving the circularity of PV from various perspectives. Including a business/economic perspective, as economics play an important role in deciding the focus for R&D, in procurement and in business investment.

Expert Interview Questions

The semi-structured interview was based around several discussion points and questions outlined in the interview protocol (Appendix C). Relevant topics included:

- View on premature replacement of functional PV modules
- Primary challenges for PV design and EoL management
- View on PV in a Circular Economy
- Feedback on the (draft) concept framework for guiding PV PLE strategies

Expert Interview Result Analysis

The notes from each interview were summarised and analysed for the relevant challenges and the mentioning of aspects related to the economics, environmental impacts, energy and materials for PV. Furthermore, their input on the concept framework was considered and suitably incorporated into a subsequent version of the framework, adding to its accuracy.

Scenarios

The combined insights from literature and expert interviews were used to make two indicative scenarios for what the impact of two PLE strategies may look like in terms of: economics, environmental impact, energy use and material demand. These were not quantified and only serve as a visual indication of what the effects may look like over a longer timeframe.

LITERATURE RESULTS

The majority of the literature found mention the potential environmental benefits and to material use by applying life extension strategies, with only one arguing against component recovery in favour of high-grade recycling (Heath et al., 2020). Only limited data was available on alternatives to recycling, towards circular business models or describing best practises (Franco & Groesser, 2021; Tsanakas et al., 2020; Walzberg et al., 2021). As found in the initial search, the focus for PV in the context of a CE revolves largely around Reuse and recycling. This was made visual in a 'word-cloud' of all keywords from the selected literature (Figure 12). Findings from literature are presented per R-Ladder strategy, and grouped by four aspects: economics, environment, energy and materials.

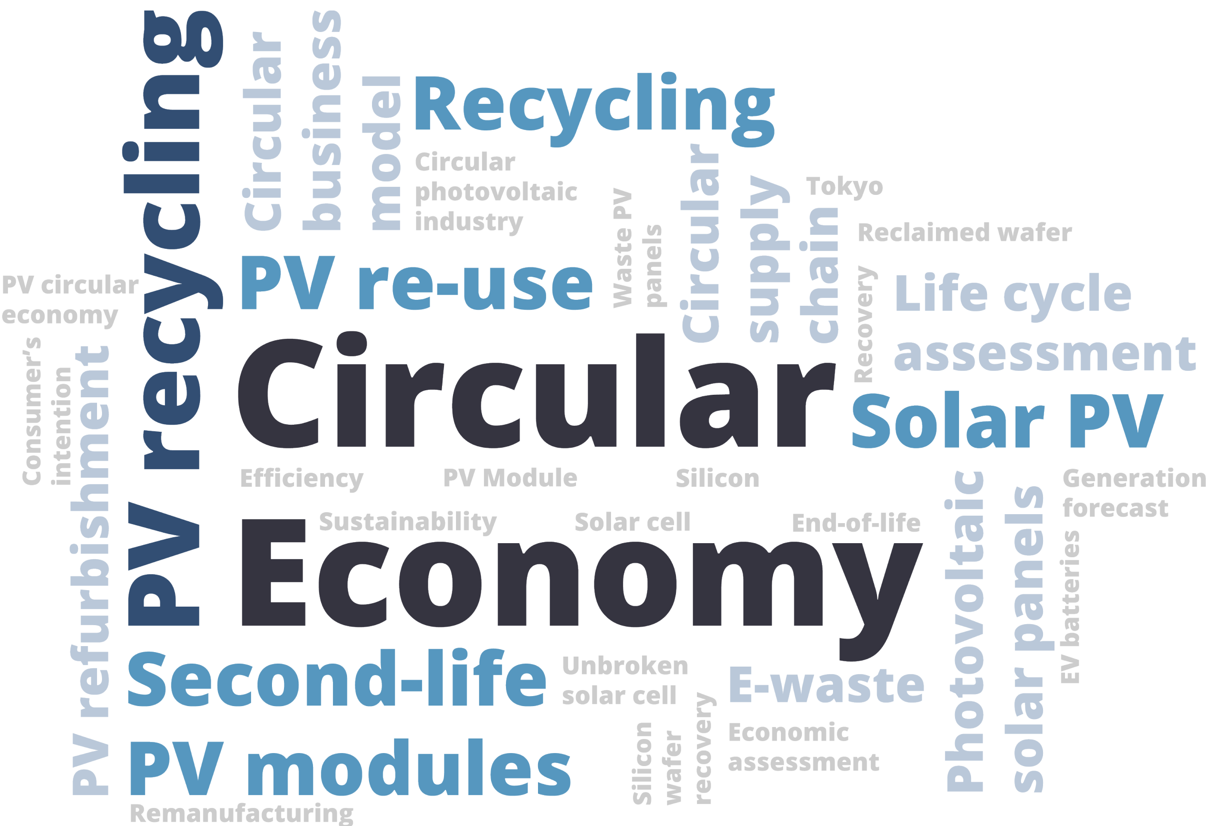

Figure 12: Word-cloud of all keywords from the selected literature, size is indicative for frequency

Reuse

Reuse describes the cases where a module, without any alteration other than demounting and reinstallation, changes hands from one owner to another to be used for the same purpose as originally intended.

Reuse – Economics

Costs are a driving factor for PV installations, as well as for the timing of their dismantling. Premature replacement is often driven by the (perceived) pay-back period of a system and feed-in-tariffs (Murakami et al., 2021). For new installations, barriers to PV adoption are primarily the upfront cost, length of payback time and installation complexities (Franco & Groesser, 2021). Since PV modules account for around 40% of total system cost, the use of cheaper reused PV modules only partly lowers the upfront costs of a system (Franco & Groesser, 2021). The exact price that could be asked for a second life PV module depends of several factors, but one study used an average of 36% compared to a new module (Walzberg et al., 2021). Combined with the lack of data on module degradation and aging, and on the failure rate, these factors negatively affect potential business cases for PV Reuse at this point in time (Franco & Groesser, 2021).

Reuse – Environment

No specifics on the environmental benefits of Reuse were mentioned, but compared to recycling before technical EoL, keeping a module in use for longer generates renewable energy for longer. This could offset less efficient electricity generation sources depending on the energy mix it replaces.

Reuse – Energy

Reuse generally means more electricity is generated due to longer use compared to recycling. It further means that none of the embedded energy from manufacturing, transporting and installing the module are destroyed (Walzberg et al., 2021). However, energy output is often used to determine the threshold of whether a module is considered “failed”, regardless of the fact that it does still output electricity (Murakami et al., 2021).

Reuse – Materials

Effective Reuse requires supply and demand to match, which only happens when a market matures (Walzberg et al., 2021). The current growing PV market can therefore not be fully supplied using second-life modules, even if the Reuse rate would be 100% (Walzberg et al., 2021).

Repair

Repair restores a PV module's functionality after it has lost its ability to generate electricity before the expected lifespan has surpassed. For Repair to succeed, services must be available, which may include diagnosis, component replacement, technical support, installation and warranty (Maceno et al., 2022). Repair is however limited to several defects including: defective frames and mounting hardware, faulty bypass diodes and connectors in the junction-box, certain backsheet defects, and in cases of potential-induced degradation (PID) (Tsanakas et al., 2020).

Repair – Economics

Repair is often performed by third-party or independent service providers without a standardised approach or aid from the manufacturer (Tsanakas et al., 2020). While at the same time, service providers require data on system performance, degradation and failures to determine the volume, age, and cost of Repair to establish whether it is worth it in the first place (Tsanakas et al., 2020). Repair costs must be kept low compared to the cost of a new product (Maceno et al., 2022). Volume plays a role in driving these costs, Repair may only be viable for large number at a time since it requires labour and experience (Tsanakas et al., 2020). These are all costs that are affected by economies of scale. Other factors affecting Repair cost have to do with how a system is installed. Integrated systems, such as in-roof systems, are only waterproof as a whole. Repairing a single module may require fully dismantling the entire system, which means more labour, time and costs (Tsanakas et al., 2020).

Repair – Environment

The use phase of PV is considered to generate the most significant positive environmental benefit (Maceno et al., 2022). Keeping a module in use for longer, through Repairing a failed module, therefore directly contributes positively to the environmental impact from renewable electricity generation.

Repair – Energy

About 80% of decommissions occur within the first four years of a module's operation and 45-65% of these are considered Repairable (Tsanakas et al., 2020). This would mean that repairing such a module adds ± 20 years of electricity generation to its lifespan.

Repair – Materials

Several circularity tools indicate that preserving or Repairing PV modules greatly improves their circularity potential (Maceno et al., 2022).

Refurbishment

Refurbishment goes beyond the capabilities of a Repair and restores a PV module to a predetermined level of quality, which may include aesthetic improvements as well. Defects that can be resolved through Refurbishment include: exchange of broken Si cells, non-destructive removal of backsheets, separation of the front glass from intact cells and the exchange of damaged EVA encapsulant layers (Glatthaar et al., 2017). However, failures such as fractured glass, cracked cells and snail-trails are beyond Refurbishment (Tsanakas et al., 2020).

Refurbishment – Economics

As with Repair, Refurbishment is often performed by third parties who require access to data about system performance, degradation and failure rates to determine whether it is economically viable to perform Refurbishment (Tsanakas et al., 2020). Another factor deemed critical is the geographic location of the Refurbishment plant in relation to the PV installation, as this affects economic effectiveness (Gautam et al., 2022). This reduced additional costs and lost time from transport. At the end of the Refurbishment process, the second-life modules may be sold for up to 70% of the cost of a new module (Gautam et al., 2022).

Refurbishment – Environment

No specifics were mentioned for environmental impacts from refurbishment.

Refurbishment – Energy

No specifics were mentioned for energy use from refurbishment.

Refurbishment – Materials

The PV-Rec concept described by Glatthaar et al. (2017) incorporates a Refurbishment option in their recycling process as part of a multi-step approach. They advocate for tailor made procedures to restore functionality before sending the modules off for materials recovery. This would prevent materials from being taken out of use before a module has reached is technical EoL. One of the challenges in those situations to Refurbishment is the great variety in module designs (Glatthaar et al., 2017). The modules that can no longer be Refurbished can however still be used as donor sources of components for restoring other modules (Glatthaar et al., 2017). Ideally these factors would be considered beforehand, where material selection considers the benefit of multiple life cycles over traditional criteria for efficiency and cost optimisation (Charles et al., 2017).

Remanufacturing

To Remanufacture a PV module, it has to be fully disassembled to separate all major components for Remanufacturing to a degree that equals or surpasses that of a new module.

Remanufacturing – Economics

Manufacturing of the cells used in c-Si modules accounts for 40-65% of the cost of the entire module (Lee et al., 2018; Smith & Bogust, 2018). Recovering intact cells through a Remanufacturing process has the potential to recover a substantial part of the value from used modules. Using these reclaimed cells could reduce manufacturing costs by up to 20%, or by up to 12,5% when Remanufactured to the same performance specification as the original cell (Deng et al., 2021).

The current lack of standardisation combined with the lack of economies of scale mean that Remanufacturing costs are still relatively high (Deng et al., 2021; Heath et al., 2020; Maceno et al., 2022; Schoden et al., 2022). Although one example shows cost parity between a standard PV module and one using reclaimed wafers, both at $0,25 per Wp (Deng et al., 2021). Another consequence of recovering an intact wafer is that the silicon retains its purity, thus retaining the value of solar grade silicon of $10 per kg compared to $2 per kg for metallurgical-grade silicon (Deng et al., 2021; Heath et al., 2020). In cases where Remanufacturing yields lower performance some expect markets specific for low-cost modules to develop where they might be used for, e.g., street lighting (Deng et al., 2021).

Remanufacturing – Environment

Closing the material loop for PV manufacturing has the potential to reduce its global warming potential by as much as 74% (Deng et al., 2021). Yet this depends on the specific technique chosen for Remanufacturing. Some processes require high temperatures, whereas others use harmful chemicals for disassembly (Heath et al., 2020; Park et al., 2016).

Remanufacturing – Energy

In c-Si cells, where the silicon wafer is a significant contributor to the total embedded energy of a PV module, using reclaimed cells can significantly reduce the energy payback time (Park et al., 2016). More specifically, the manufacturing a module from virgin resources requires between 300 and 375 kWh, with the cell making up 60% of the energy used (Deng et al., 2021). Thus, offering a potential energy saving of between 180 and 225 kWh in manufacturing.

For thin-films, the majority of manufacturing energy is needed to make glass. Switching out the other components during a Remanufacturing process, usually the ones that degrade fastest over time, would preserve the embedded energy from glass manufacturing (Schoden et al., 2022).

An advantage specific to Remanufacturing is that it can perform better than the original, as teething problems are known by the time the first modules return for Remanufacturing (Schoden et al., 2022). This can result in generation over generation improvements while using largely the same core components. One example of a relatively old PV farm showed an efficiency improvement from Remanufacturing. A system built in 1983 was disassembled, 74,5% of cells were successfully extracted and Remanufactured and showed a 13% efficiency compared to 8% for the original modules (Bombach et al., 2006). Another example showed a small discrepancy between Remanufactured and new, with efficiencies of 18,5% and 18,7% respectively (Lee et al., 2018).

Remanufacturing – Materials

To maximise the Reuse value of recovered components, they have to be recovered in their entirety, not be contaminated with other materials and be free of residues (Einhaus et al., 2018). The encapsulant layer plays an important role as a major contaminant. One subset of c-Si technology uses an edge-seal as opposed to traditional EVA encapsulant sheets, and allow for easy recovery of intact PV glass and copper tabs connecting the cells (Einhaus et al., 2018). However, most cells do break during disassembly.

In traditional c-Si modules, the cells tend to break during thermal treatment where the EVA generates gassed that produce pressure between the cell and glass (Park et al., 2016). In those cases, there is a decision to be made for the recovery of the cells or recovery of the glass, since fracturing the glass helps reduce the internal stresses from thermal disassembly (Lee et al., 2018).

Residue from the EVA encapsulant may be mechanically removed, depending on the thickness of the cell (Park et al., 2016). Before the 1990's cell thickness was around 400 μm whereas today these are ± 180 μm (Heath et al., 2020). This allows for more material to be removed from older cells compared to newer ones, while additional thickness also adds to the recovery yield of intact cells (Bombach et al., 2006). Any cell over 200 μm in thickness is less likely to break and can often be re-etched for cell Remanufacturing, with one example showing a yield of more than 97% (Tao & Yu, 2015). Another example using a pyrolysis process in a conveyor belt furnace was able to recover more than 80% of cells intact (Lee et al., 2018).

Other Circularity Factors

Other factors, not befitting one of the above categories, were described as important to the circularity of PV by the authors. These include the attitude and acceptance towards second-life PV modules as an important factor to its adoption (Murakami et al., 2021; Walzberg et al., 2021). This affects decision-making for investments in new PV installations and the possible choice for using second-life modules. Combined with limited information about performance over time, makes second-life PV a potential risk. For degradation there are generalised numbers available such as 0,4-0,8% per year for c-Si and ±0,5% for CdTe thin-films, but not specific to one module type provided by their manufacturer (de Oliveira et al., 2019; Jordan et al., 2016; Wilson et al., 2020).

Similarly, data on failure rates help guide investment decisions. While general estimates of between 0,15-0,25% per year are mentioned, this may vary depending on the specific conditions under which the installation has to perform (Tsanakas et al., 2020). And finally, for Repair, Refurbishment and Remanufacturing, a manufacturer would have to keep spare parts in storage to enable these processes over one or multiple life cycles (Heath et al., 2020).

Literature Conclusions

Examples were identified for each of the PLE strategies that were part of the literature search. Each of those strategies have their own set of conditions for which they function, primarily based on the physical condition of the module and the remaining performance. This is followed by economic factors, which dictate whether a strategy may be considered worthwhile. It is currently difficult to formulate a viable business model for these PLE strategies. This is partly because PV is still a growing technology that needs time to mature. With the current growth of installation and the lag-time between installation these volumes are expected to grow. Eventually, the larger volumes may offer the benefits of economies of scale to reduce the cost for each of these processes.

In all cases, the PLE strategy was deemed to have a positive effect on the environmental impact. The use-phase was described as the major contributor of positive change, as the long use of PV systems replaces an energy-mix that contain fossil fuels. Furthermore, offsetting the impacts from manufacturing, the Reuse of components has the potential to reduce energy demand from manufacturing. For c-Si PV technologies the main contributor to manufacturing energy demand is the silicon cell. For thin-films the main impact is from the glass substrate on which the other materials are deposited. In deciding on the specifics for a Remanufacturing strategy, if the component selection for recovery is based on the embedded energy, then the selected components may differ based on the PV technology. Each strategy thus has its own benefits and conditions, which were further explored in the case studies and during the following interviews.

CASE STUDY RESULTS

Analysing three practical examples of PLE strategies aims to answer sub-research question 2. Each case is introduced, followed by insights from their specific application of the chosen PLE strategy. It describes the reasoning behind the chosen strategy, impact on PV resource use, benefits, and challenges specific to their strategy and their view on current PV design. The differences in approach and impact are subsequently compared.

Reuse

Marktplaats – Informal Reuse

Marktplaats is a Dutch platform for buying and selling of used products and goods (Marktplaats, n.d.). One of their product categories are PV modules, which may offer an insight into the composition of the Dutch Reuse market for PV.

In total 49 out of the analysed 117 unique advertisements provided information for the number, performance and age of the modules (≥ *Vind Zonnepanelen | Zo Goed Als Nieuw in Zonnepanelen En Toebehoren Op Marktplaats*, n.d.). Average performance for the total 1080 modules was 231 Wp. Performance distribution shows a spread from 150 Wp to 410 Wp (Figure 13).

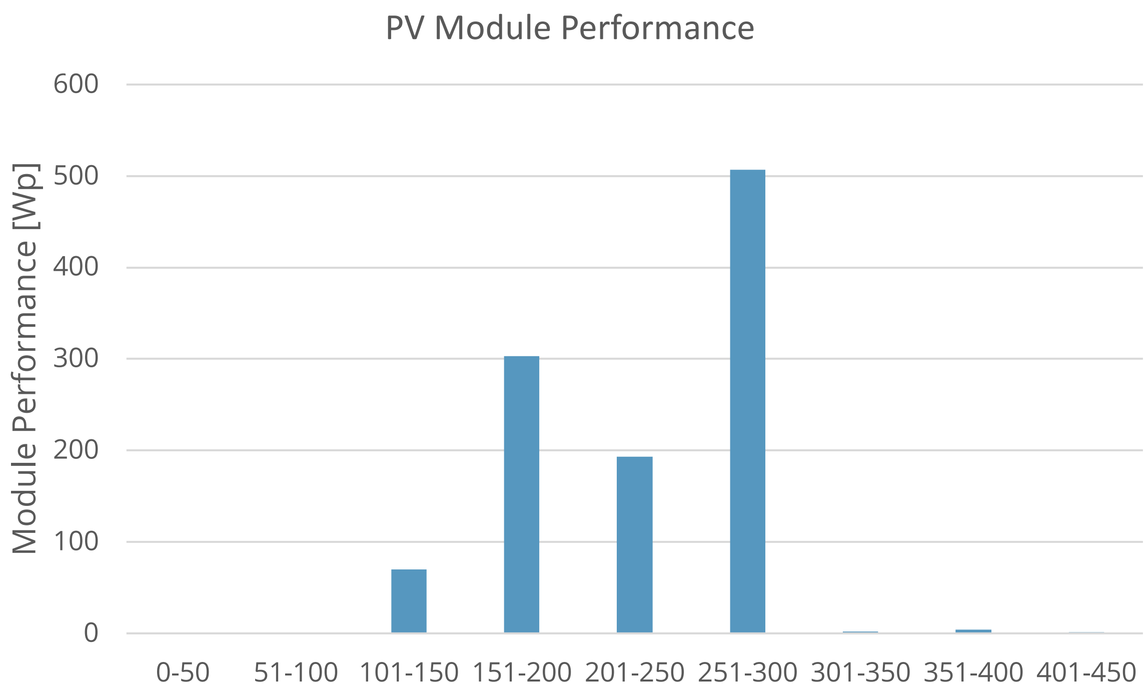

Figure 13: Number of PV modules listed on Marktplaats, sorted by performance in Wp

Average panel age was 8,75 years, with a spread from 1 to 21 years (Figure 14). These results show that most modules are rated for over 200 Wp in power output, with a combined 250 kWp of capacity. The age of these modules is primarily between 5 and 12 years, resulting in a remaining lifespan of between 13 and 20 years assuming an average lifespan of 25 years. The outliers with the shortest lifespan were mostly modules that came pre-installed on a newly developed home. Some new developments that were built under the BENG-requirement ('Bijna Energie Neutrale Gebouwen' or nearly energy neutral buildings) are required to generate a certain percentage of the expected electricity use themselves via renewables (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2019). Construction companies, in those cases, have installed only the bare minimum required number of modules without giving the new owners the option to opt for a larger system. Leading to the sale of nearly new PV modules.

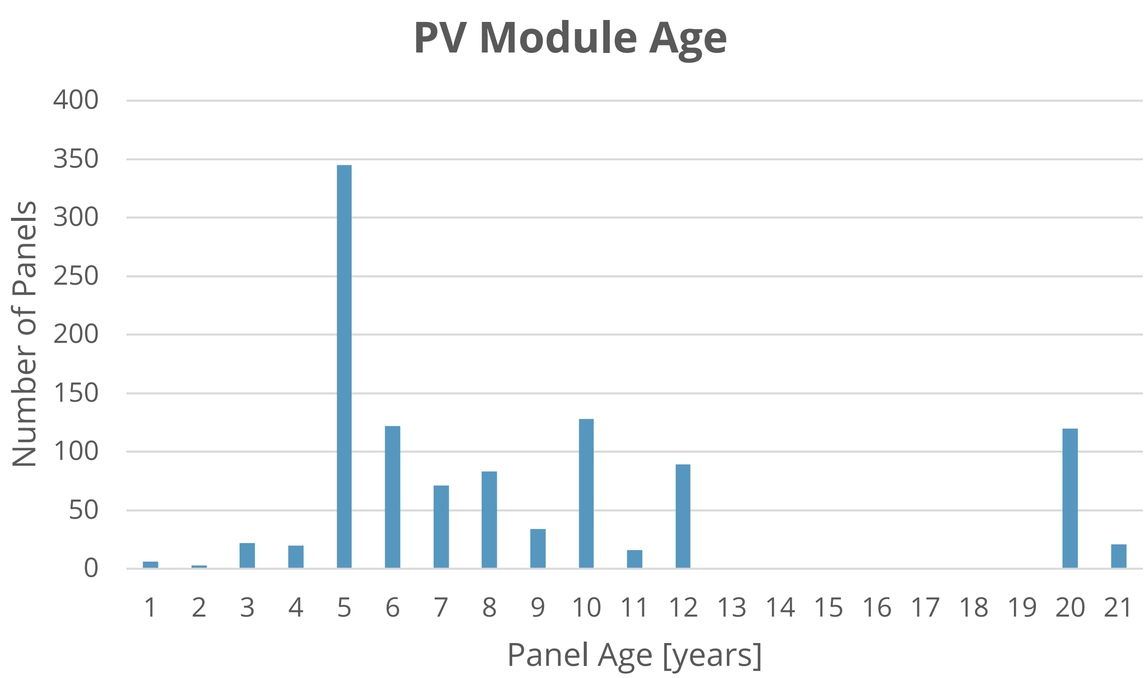

Figure 14: Number of PV modules listed on Marktplaats, sorted by age in years

Lastly, the reason for selling the used PV modules was noted. Out of the 49 advertisements that provided relevant data on the modules themselves, half did not mention why they were selling. In 31% of cases, the used modules were sold due to an upgrade to a new system with a higher capacity. In 10 % of cases, the modules were sold after a renovation. These included cases where a dormer was installed or a roof replaced, leaving less space for these PV modules. In 8% of cases, modules were sold as surplus.

ZonNext – Formal Reuse

ZonNext was founded on the knowledge about the shortcomings of current PV recycling methods. No PV recycling exists in the Netherlands to date. Discarded modules are mostly transported to Belgium for bulk recycling, where the reclaiming materials are downcycled to lower value uses in, e.g., construction. Eventually, high-grade recycling of PV materials for Reuse in new PV technologies would be preferable, but this needs further development. In the meantime, the potential waste challenge from EoL PV modules keeps growing, as they also state in their whitepaper and impact report (Sungevity, n.d.; ZonNext, 2021). Extending the lifespan offers a way to use existing materials more effectively, which is something no other party was doing at scale.

The used modules are collected in a collaboration with WEEE NL, who are responsible for the collection of one third of all discarded PV in the Netherlands currently. Together with Refurn, which is part of WEEE NL, each individual module's performance is characterised using flash-testing, given a TUV certification and a warranty (ZonNext, n.d.-c, n.d.-a). In their selection process modules of up to 15 years and with a performance of around 220-250 Wp were considered sufficient for Reuse as disclosed in an interview with ZonNext (Appendix G).

Modules originate from organisations often with larger installations, that are replaced in favour of newer technologies or discarded. Their willingness to offer these up for Reuse was described as high, given that they were given a new positive purpose. Some even promised future deliveries of modules that are still in use. The new use cases include installations for housing corporations to aid inhabitants living in energy poverty and schools where they provide an additional educational benefit (ZonNext, n.d.-b). They further contributed panels to De Ceuvel in Amsterdam, which is a breeding ground for pioneers in the field of sustainability and creativity (De Ceuvel, n.d.-b, n.d.-a). And recently they collaborated with Tesla and Sungevity to deliver PV modules, batteries and inverters to Ukraine to provide emergency power (Clean Tech Regio, 2022).

The examples of second-life use cases are all meant to offer electricity to those who need it and those who cannot afford a new PV system. ZonNext, as a non-profit, only charges for the costs of logistics, testing and re-certification. Although these costs are low compared to new modules, they mentioned that the business case for second-life PV remains a difficult one. For now, they rely on subsidies, making the future economic situation a precarious one.

Repair

Out of 237 organisations affiliated with Holland Solar, a representative organisation for the Dutch solar industry, only 3 specifically mention Repair (Holland Solar, n.d.) (Appendix D). However, very few details were given on what was meant by Repair. It was often combined with general 'maintenance', which could include anything from module cleaning to inverter readouts. This shows that, currently, Repair is not a primary focus for the Dutch PV industry.

Boldz Repair

Boldz was founded realising that substantial volumes of used PV modules were already coming off rooftops in the Netherlands but had no clear place to go to next. Many of them were only 5 years old and still functional, but some showed small defects, as was stated in an interview with Boldz (Appendix F).

Initial Repair on glass-foil c-Si PV modules seemed promising but demonstrated several challenges at low volumes. Finding spare parts, although possible, was deemed not viable for a handful of modules at a time. Some Repairs required specific OEM replacement parts that could not be substituted. The Repaired modules were never sold on their own, but they were used in their own product the 'Powerbank' (*Wat we doen | Boldz*, n.d.). Further techniques for the Repair of glass-glass modules are being developed, expecting this sub-category of c-Si modules to gain significant market share over the coming years.

Repurpose

Repurposing includes forms of Reuse for a different function compared to the original functionality. For an electricity generating technology this seems incompatible given its primary function is generating electricity. Using it for other purposes would potentially defeat that purpose, however one example showed the potential value of reusing PV in a different way compared to rooftop or field installations.

Boldz Powerbank

Aside from developing Repair techniques, Boldz creates a picnic table Repurposing a PV module together with Refurbished batteries into a physical representation of what is possible in a Circular Economy (Boldz, n.d.). As stated earlier, modules coming off roofs often did not have a clear pathway. This would be an example of one possible pathway for used modules to extend their lifespan and to keep generating renewable electricity.

One important criterion, as mentioned in the interview with Boldz, was to create a viable business model for their circular application of PV modules. They did not want to rely on subsidies for their existence, but rather to show how it is possible to combine a viable business case with a product that would otherwise be discarded as waste. The importance of economic factors for circular PV applications was shown in the coded interview results as well (Appendix F). The Boldz table is an example of how PV can be beneficial, even though the primary purpose is now a table first and a PV module second. While their specific implementation makes less efficient use of the panel’s capabilities, it offers a notable indirect effect as a showpiece as a circular product application and a conversation starter on effective use of resources.

They went on to state that second-life PV has a place in the Netherlands, but that one must consider alternative approaches to the way these modules are implemented or integrated into their environment. In the traditional PV systems in the Netherlands, space is often constraints and owners want to maximise the generation capacity of the available surface area. These spatial constraints do not exist everywhere and to the same extent, leaving roof for solutions that are less than perfect depending on the trade-offs made.

These trade-offs come back in the design of these modules. One module might be very hard to disassemble or Repair but offers a very long lifespan. Modular approaches might not achieve the same lifespan or suffer more defects over their lifespan. But these are much easier to address compared to the other module. And there are also cases where a shorter lifespan might be beneficial, such as locations where a roof is schedule for renovation in a few years’ time or on buildings that are planned to be demolished.

Case Comparison

Considering the four aspects previously used to categorise findings, the economics of Marktplaats hint to an affordable alternative to a new PV system. Second-hand PV modules offer an environmental benefit by extending the lifespan of functional modules, by changing hands from one owner to the next. Since a significant portion of these modules were offered because to an upgrade, these modules are likely to replace part of an energy-mix that utilises fossil fuel sources. This would increase the share of renewables in that overall energy-mix. Furthermore, they have a positive impact on materials demand since no new modules must be manufactured to supply the needs of those purchasing second-hand PV modules.

Regarding the economics, ZonNext only charges for the logistics, testing and re-certification. This provides a more affordable alternative in specific use-cases such as for schools and housing projects. As is the case for modules exchanged on Marktplaats, ZonNext extends the use-phase, potentially replacing a partly fossil fuel powered energy-mix. This provides beneficial effects for both energy generation and environmental impacts. The exchange of modules requires limited extra materials for transport, storage, and installation.

Compared to Marktplaats, this Reuse case is centrally organised and has a focussed target group or targeted use context, whereas Marktplaats is decentralised and primarily consumer-to-consumer. ZonNext works with larger volumes of modules at a time compared to individual sellers on Martplaats. This caters to both the supply and demand side of business-to-business trade, as both offer and want larger volumes of modules.

Boldz addresses two PLE strategies for PV; Repair techniques and the Repurpose of used PV modules. Between these strategies there is some overlap, as repaired modules are repurposed for their table. One of their goals was to offer an economically viable alternative to discarding and recycling. They extend the lifespan of the PV module to continue the generation of renewable electricity while facilitating further conversation and discussion on what could be possible in a Circular Economy. Many of the materials used in their table are reclaimed, Refurbished or Repurposed, requiring mainly time and effort.

Case Study Conclusions

Three cases of practical PLE strategy implementations were identified and analysed. All showed potential pathways for extending the lifespan of PV modules, to continue generating renewable electricity offsetting the existing energy-mix. They contribute to the reduction of environmental impacts by avoiding emissions and the potential environmental harm from improper EoL treatment. Material demand for new PV module manufacturing may be delayed through Reuse and by restoring functionality in defective PV modules. The extent of these impacts was not quantified, due to a lack of data and uncertainties about the remaining lifespan of these modules.

The fact that most of these examples addressed PLE strategies for Reuse, for PV modules that were still functional did stand out, as was the case in the literature search results. Repair was part of the approach from Boldz but was not a viable standalone business. Examples for Refurbishment and Remanufacturing were not found. The reason for their absence is likely caused by the difficulty of disassembling current PV modules in a way that enables clean recovery of intact components through an economically viable process. This confirms some of the main challenges to PLE strategies that the literature review already touched upon. The focus of the life extension approaches as shown addresses an immediate gap that may only offer an intermediate solution while technology for recycling and other strategies develops.

EXPERT INTERVIEW RESULTS

Several experts were interviewed to answer sub-research question 3. While all interviewees specialised in PV, they had different backgrounds; from research-, industry- and policy perspectives. Their perspectives were noted and summarised. Key insights are discussed, grouped by the four categories used throughout this study: economics, environment, energy, and materials. They also provided additional information that was used to create possible circular pathways for used PV.

Expert 1

The first expert was knowledgeable on c-Si technologies and offered a research perspective on the challenges and possibilities for PLE strategies for PV (Appendix H). While generally in favour of long use and PLE implementations, several challenges were noted to such an approach. Among the main challenges for PV were mentioned: higher efficiency as they reduce costs as well, integration to make PV invisible for improved adoption, and the switch to sustainability and circularity.

Economics

The primary reasons for (early) replacement of PV systems are economic. These are replaced after ±10 years by newer systems that offer more value in the form of higher yield per square meter. When discussing the economics of PV, one should consider the value rather than the price. Integrating PV into infrastructure, buildings and mobility increases its value. PV has reached a point where it is inherently affordable, which is why the focus should be on other aspects such as increasing public support and the ecological aspects of the value proposition.

Environment

From a Life Cycle Analysis (LCA) perspective, CdTe should be the most sustainable PV technology. This considers factors such as the energy pay-back time but may not sufficiently take into account the potential harm if cadmium is released into the environment. Alternative design approaches for c-Si PV modules did show potential for increased sustainability through design. NICE-modules (New Industrial Cell Encapsulation) only use an edge-seal and negative pressure as opposed to an EVA encapsulant. This would lower the need for energy and chemicals during disassembly.

Energy

One example of Repair could be to open the back of a glass-foil c-Si PV module to redirect a broken cell. While that one cell would no longer generate electricity, the rest of the row would. Such as Repaired module could be reused in a context where energy generation density is less of a concern.

Materials

Ideally, PV modules would be recycled at EoL, in a closed loop and to a degree that the materials can be reused in other high-quality applications such as new PV or in battery technologies. Current recycling can still be described as downcycling since the materials are reused in a lower value application. One expectation is that remelting and regrowing of a silicon ingot are unavoidable after recovering the PV cells. Unless different processes are used, and modules are designed specifically for recycling. Those would utilise an encapsulant that can be released after applying an external trigger.

When viewing Reuse options, one consideration could be the level of solar irradiance in the Reuse location to maximise electricity generation over the remainder of the module's lifespan. However, sending these modules of to, e.g., an African country would require transport and result in a lack of overview and control over what happens with the module at the end of its technical life there. Another option for Reuse is to consider use cases that would benefit a shorter PV lifespan, such as buildings scheduled for renovation or other temporary sites.

Considering Remanufacturing for example, it is worth noting that cells from the early 90's were about double the thickness of today's cells. Processing, using newer techniques can yield a more efficient cell, but the silicon quality is likely lower compared to today's silicon quality. By remelting and purifying the silicon, it would theoretically be possible to make double the number of cells from the older, thicker cells through recycling. While Remanufacturing is doable on a lab-scale, it is questionable whether it can be scaled up to, especially regarding the recovery of intact PV cells.

Materials challenges differ per technology type. CIGS is now only a small player, partly because there are not enough resources available globally to make enough CIGS PV to significantly contribute to the energy transition. 1TW of CIGS capacity would exhaust global indium resources. Upcoming Perovskite modules use very few CRMs, but it does contain lead and tin in an indium-tin-oxide layer. Lead is considered toxic, while tin is listed as a conflict mineral by the EU (European Commission, n.d.).

Expert 2

The second expert was knowledgeable on c-Si PV technologies and offered a research perspective (Appendix I). The discussion touched upon several challenges specific to our western society and the way aesthetics contribute to our acceptance of PV in our direct environment.

Economics

PV was compared to the process of purchasing a car, where in western society, people tend to prefer the latest and greatest. This consumerist approach contributes to the early replacement of PV, even though PV is generally designed and built to last.

Environment

In the ongoing development and search for alternatives to silver, due to its cost and potential future supply constraints, copper is considered as a replacement. However, the application of copper in PV Remanufacturing requires chemicals. The resulting dirty water needs collecting and cleaning and may pose a risk to the environment.

The major culprit to a c-Si PV module's carbon footprint is the silicon wafer. One challenges then becomes the gentle recovery of these wafers. Since the interface between cell and encapsulant is hard to detach, the most common methods nowadays are to crush and burn the modules to burn off the encapsulant to detach it from the glass and wafers.

Energy

No insights specific to energy challenges for PV were noted.

Materials

CRM acquisition is one of the major challenges for PV going forwards, as it is used for thin-films and in multi-junction PV technologies. The contacts in c-Si PV are made of silver, and although only 10 mg of silver is needed per cell, scaling it up to the capacity needed for the EU energy transition eventually would grow this demand to half of the global silver market.

Expert 3

The third expert was a PV module manufacturer and was able to offer business and industry insights towards the challenges of circular PV (Appendix J). They advocated for possible legal requirements for the minimal lifespan of PV modules to ensure quality and lower negative impacts from manufacturing and EoL management.

Economics

One question, regarding the Repair of PV modules, is that of legal responsibility. When a third party repairs a known-brand module and sells it, who is responsible and how are they being kept responsible for, e.g., certification costs that the manufacturer paid? Under current regulation the third-party Repair service provider would not have to pay for this.

For Reuse the question is whether it is currently economically viable. There are labour costs attached to dismantling a PV system that should be considered. Even if it might contribute to delaying the upcoming waste challenge. Stichting OPEN, who are currently responsible for the collection of removal fees, might not be prepared for removal and EoL processing. With increasing volumes come increasing costs.

Environment

Material choices for PV design and manufacturing affects sustainability factors. For example, the inclusion of lead containing solders and Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) poses concerns for the environment due to their toxicity. Similarly, the use of antimony in PV glass, while making it more transparent, is toxic and not usable in many other cases.

Energy

Global installed capacity is at ± 1TW and took over a decade to achieve. To reach future foals for our energy transition another 1 TW would have to be added in additional capacity annually. Since manufacturing PV cells is energy intensive, this raises concern whether there is enough energy available to make these PV cells and modules. Up to a point where entities are considering constructing nuclear power plants to provide the energy needed for PV manufacturing.

Premature replacement of modules could further add to the energy demand of new modules, however, there have been cases of upgrades where the used modules were moved to a north-facing side of the roof rather than being send off for recycling. Even though that would be a less than ideal orientation on the northern hemisphere, modules still generate electricity from indirect or diffuse sunlight.

Materials
Current developments for circular PV focus, among others, on reclaiming glass without contaminants, for Reuse or remelting. A new encapsulant, as opposed to current thermosets, should behave more like a candlewax and be able to glue multiple times. The chemical composition of such an encapsulant is now in development. Aside from the easier removal of the PV glass, it would aid the recovery of silicon, copper, and silver. This would enable new Reuse pathways that were not possible prior due to the encapsulant contamination of these materials.

Expert 4

The fourth expert did research on safe and sustainable PV for the RIVM (Rijksinstituut voor Volksgezondheid en Milieu) (Appendix K). With the effects the environment and public health in mind they advocated for using PV for as long as possible (Hof et al., 2022). Their focus was primarily on the environmental effects.

Economics

No insights specific to economic challenges for PV were noted.

Environment

Early retirement of a PV system, especially for large scale installations, is often determined by external factors. These include the lifespan of the inverter, which is between 10 and 15 years, and the duration for which a land-use permit was provided. The difference between a 15-year module lifespan compared to 30 years, in terms of environmental impact, is large.

Energy

To extract as much electricity from used modules as possible, one approach is to send them to places with higher irradiance than the Netherlands. Those could be within the EU, or in countries in northern Africa. In the latter case this does come with the risk of losing control over EoL processing.

Materials

Recovering the PV cells appear to be the low hanging fruit to gain the most immediate environmental benefits. In c-Si modules, this is where most of the CRMs are located. Recovering those is the most direct route to reducing the impact per kWh.

Expert 5

The firth expert contributed to the foundation of a buyer group for more sustainable PV (Appendix L). They offered a policy and procurement perspective on today's challenges for decision-makers at governments and organisations purchasing large amounts of PV. Part of their work is to set criteria, other than price and performance, to consider factors such as lifespan, carbon footprint and working conditions in the module's country of origin.

Economics

PV replacement is often dictated by external factors, including economic ones such as subsidies. These are often created for 15 years; business cases are based around such regulations. Another factor is that of land use rights, these are similarly for a limited timespan affecting the business model for PV on such a location.

Developing a business case for second-life PV modules is even more difficult. All other costs, for labour and balance of system, are relatively higher for a system with a lower efficiency. For circular business models to succeed there should be a mechanism that rewards sustainable behaviour. Steering purchasing behaviour could send a clear signal to PV manufacturers about the importance of requirements other than cost and performance. By continuously purchasing affordable PV from, e.g., China, the development of more sustainable PV modules will not be stimulated.

In cases of PLE turned into viable business case, it often concerns small-scale solutions. It is not always clear who is responsible for the resulting second-life modules. This creates additional risks for, e.g., PV installers who cannot or may not want to guarantee long-term operability of used PV. They would likely prefer working with well-known brands that they trust and sell as many modules as possible. Existing business models and the business models needed for PV life extension often have conflicting interests.

There is an example of a business in Germany that stockpiles older modules to offer them as replacements for failed modules in existing systems. However, these are much more expensive compared to new modules, making this a difficult choice between keeping an older plant operational by replacing one or several modules or to upgrade the entire system.

Environment

PV producing countries, such as China, use a lot of cheap coal power for manufacturing. This gives these modules a relatively higher carbon footprint, lengthening the energy payback period. Supply of modules with a comparatively low carbon footprint is not high enough, which may have consequences for the footprint of the technologies used for the energy transition.

Energy

No insights specific to energy challenges for PV were noted.

Materials

CRM are not viewed as an issue by some. They are used in low amounts are sometimes deemed replaceable. However, this further lowers the incentive to recover them at end of life. Nowadays used modules are send to Belgium for processing, where they are downgraded for use in construction.

As an alternative to recycling, some argue for sending used modules to Africa after their first use. However, that means they will eventually reach e-waste status there. It is uncertain whether they will be processed in a way that materials are adequately recovered.

An example of a different approach, from a design perspective, is that of Solarge. This Dutch PV manufacturing company makes a plastic PV module. Although it has a shorter lifespan compared to modern traditional PV modules, it is much easier to process the at EoL and to reclaim the valuable materials.

Expert 6

The sixth interviewee was an expert on PV devices at TU Delft and offered research insights into the challenges and opportunities in the long-term for the application of PLE strategies for PV (Appendix M). They noted the importance of investigating alternatives to current recycling capabilities for dealing with PV modules already in use.

Economics

The cost share of PV modules compared to the other components of the system is now <50% of the total. Yet their performance is the main source of income, all other parts facilitate the electricity generation and distribution. Reusing 10-year-old modules may be feasible, but it depends on the specifics of a given technology type. The continuous technological development makes newer modules a more interesting alternative. The slowing development rate may aid the adoption of Reuse. However, the other costs such as installation and balance of system costs remain. An alternative could be to offer easy plug & play systems for consumers to use, e.g., on their balconies.

Most of the new modules in use are made in China and shipped to the EU. Logistics make up between 5% and 10% of the price per Wp. Local manufacturing could reduce the transport costs, but other costs related to manufacturing are more expensive in the EU. Moving PV manufacturing to the EU would therefore not necessarily make it cheaper than importing the modules from China.

Considering the EoL processing of PV modules in the EU, there are two important factors to the viability of a business case for recycling. The first having to do with what you can pay in recycling. By offering compensation for the processing of EoL PV modules there is a stronger incentive for organisations and individuals to hand in their EoL PV. If they must pay for the privilege of having their modules recycled, it may be likely that they will look for alternatives. The second question has to do with volumes: can you get sufficient and continuous volume in to keep a factory running for ±50 weeks of the year? With the current waste volumes an average recycling facility would run out after just 4 weeks. These metrics are likely to apply to life extension strategies as well.

Environment

No insights specific to environmental challenges for PV were noted.

Energy

To achieve the renewable energy targets set by the EU, we would need around 1-4 TW of annual PV capacity to be manufactured and installed. This requires a lot of energy to make. The advantage of PV is its short energy payback period of ±2 years or down to ±1 year in Spain or countries with similar solar irradiance. The PV manufacturing industry could power its own electricity needs if the manufactured modules are used for a long enough period of time.

Materials

The reason to recycle PV modules is for the valuable materials and for the fact that they contain lead. Looking at one of the valuable materials used in PV; silver, the continual use of it for PV may cause serious supply constraints. Last year already ±10% of the global production of silver was needed to manufacture PV modules. While the PV industry is lowering its material intensity for silver, the decline in use per modules is not fast enough compared to the growth in the number of modules manufactured.

About 10 years ago, PV modules contained roughly double the amount of silicon and 70% more silver compared to modules manufactured today. From a materials recovery perspective, reclaiming these metals can have a significant impact on the materials supply. Especially when one older PV module contains the materials to manufacture two new modules, with higher performance. However, it must be noted that with the decrease in materials per modules, the incentive to recover them also goes down.

Knowing exactly what materials, and in what amount, are present in each module would be valuable information towards this end. Currently, this is often still unknown up to the point of opening a module up. A solution to this could be to have a QR (quick response) code or to use RFID (Radio-Frequency Identification) to provide a full bill of materials (BOM) to PV EoL processors. Something that would be equally useful for the PLE scene, where Repair and component information could be included with such a code or tag. Although this is often information that a manufacturer would rather keep secret.

In the current PV industry, an intellectual property secret can only be kept of ±1 year. Once the technology is out in the field, in use on rooftops and other installations, these secrets are impossible to keep. Together with the rapid technological development, keeping a technology that would be considered outdated after just a few years a trade secret has no real value. After a period of around 5 or 10 years there would be no real reason to keep the BOM a secret. Sharing the information through a code or tag after such a period would be beneficial to PLE practitioners to extend a module's lifespan or to recyclers to know what potential value they can recover from a given module.

Considering multiple PV lifecycles, more technological development is needed. PLE strategies would be possible, but it might take another 30 years for them to reach their true potential. The Reuse of PV glass should not be an issue going forward, depending on the ability to remove it without other material residues. Frame sizes would need to be standardised to allow them to be reused multiple times. And the Reuse of cells should also be possible. Even when some material must be removed to account for thickness and doping layers.

Interview Conclusions

Six PV experts were interviewed with backgrounds in research, industry, and procurement and policy. Their insights were used to answer the third sub-question regarding the interplay between PLE strategies, material use and the energy transition going forward. Longer use of existing modules benefits electricity generation capacity and environmental impacts from offsetting an existing energy-mix, as was stated by both a research- and industry expert (Appendices J & K). Extending the lifespan of defective modules through Repair was deemed possible but may require a use-context where space is not constrained (Appendix H). Other strategies such as refurbishment and remanufacturing were deemed more difficult, which matches the findings from literature.

One researcher noted that recycling would be preferable in many cases, and in some cases even unavoidable (Appendix H). The unavoidability of remelting the silicon metal for example, depends on the quality of the reclaimed cells and whether they can be recovered intact. Module design was mentioned as the main culprit hindering easy disassembly, with the encapsulant being the primary reason, as was stated by both researchers and an industry expert (Appendices H, I, J & M).

Materials selection was another important factor with far reaching consequences to not only performance and costs, but also to the recoverability of other materials. Furthermore, it puts additional pressure on the supply of, among others, silver, and indium (Appendices H & I). The choice for a particular encapsulant affects the ease of performing PLE strategies that require some form of disassembly, and the ability to recover components and other materials from a PV module at EoL. These far-reaching consequences from the encapsulant material was also found in literature, which resulted in several recovery effort to make a trade-off between reclaiming one component over another.

The consensus was that PLE strategies do offer benefits to energy generation, environmental impacts, and material demand. The circumstances and barriers differ per strategy. While Reuse benefits renewable electricity generation, it does not have a strong business case (Appendices H, I, L & M). This message was echoed by the case of ZonNext in the Case Study analysis. Repair, Refurbishment and Remanufacturing are hindered by materials selection and current module design (Appendices H, I, J, L & M). While PLE strategies may play a larger role for PV in the future, more research is needed for these to be applied at scale.

CONCEPT PV PLE FRAMEWORK

PV R-Ladder Flowchart

With the first PV modules coming back from their first use cycle, it is often not clear what pathways could be taken to maximise the potential of these modules in terms of electricity generation, materials use and environmental benefits. The concept PV PLE Framework (Figure 15) offers a series of alternatives to current recycling, with the intent to maximise the recovery of energetic- and material value embedded in existing PV modules. Keeping a module in use for as long as possible has the largest potential for positive impact by offsetting electricity generation with fossil fuel sources in the mix.

The R-Ladder aims to retain value by adding as little extra energy and material to an existing solution as possible. The concept PV PLE Framework was based on this principle. The primary focus was on c-Si PV technologies, due to their large market share and the relatively large energetic and environmental impact of the cells.

PLE pathways

Modules are to be inspected on physical condition to determine their potential pathway. Damage deemed beyond Repair is considered, offering a pathway for materials recovery that would ideally be reused in a closed loop for the manufacturing of new PV or other high-quality applications such as battery production.

Modules with broken glass may still offer a viable source of usable cells, as broken front glass was found to reduce the yield of cells by around 4% (Bombach et al., 2006). Other defect-pathways were selected based on literature findings and insights from PV experts during interviews (Glatthaar et al., 2017; Tsanakas et al., 2020). Undamaged modules end up at the bottom of the chart, headed for Reuse or Repurpose pathways.

The physical condition is followed by performance criteria to establish which pathway is most suitable for a given module. For Remanufacturing, Refurbishment and Repair these criteria are expectations of the relative performance after the module has undergone that process. For Reuse or Repurpose pathways, those are based on the performance of an incoming module, as this will not be altered within those processes. Values for the criteria are based on literature and input from PV experts (Deng et al., 2021).

Following the performance criteria, the modules are further directed based on the economic factors affecting the expected value of the module compared to new. Economics were found to be a determining factor in the decision-making process for acquiring new or second-life modules. Cases where the expenses are deemed too high for a given PLE strategy are sent to Repurpose, where they module may still offer benefits by integrating them into infrastructure or by applying them in areas where the generation density is less of a concern. Ideally with the intent for those modules to be effectively processed once they do reach their technical EoL and no longer fit the criteria. Low-performance modules may still be used as feedstock for Remanufacturing, depending on the ability of a Remanufacturing process to upgrade the performance of the low-performance cells.

Incoming modules were specifically described as modules at the end of a use cycle, as within a CE context these modules would circulate through the available PLE strategies several times before being processed through high-grade recycling. The outgoing end results are next-life or next-use modules, as these might already be on their third, fourth of higher use cycle.

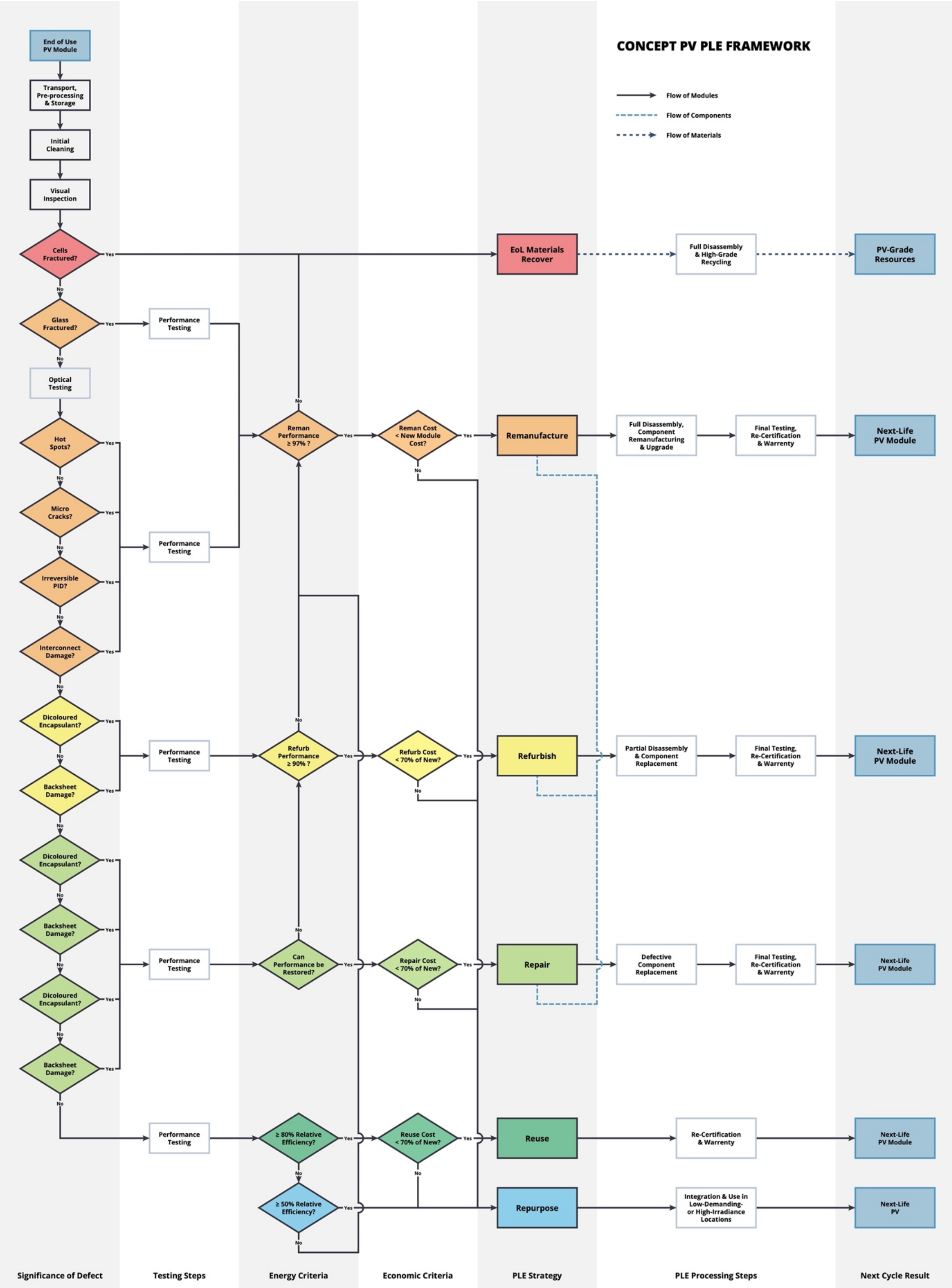

Figure 15: Concept PV PLE Framework

INDICATIVE SCENARIOS

Following possible pathways from the Concept PV PLE Framework each option has a different impact on the four aspects use throughout this study: economics, environment, energy, and materials. Two of these pathways were explored in scenarios meant to give an indication of the various impacts these strategies may have. These were not quantified due to a lack of sufficient data gathered throughout this study but give an impression of the potential impacts from the perspective of the author. All scenarios were made for a 30-year timespan, which roughly equals the current lifespan of a PV module. Within this timeframe, the effects of premature replacement can be seen as compared to the PLE scenarios.

Residential System Upgrade & Reuse

The baseline used for this scenario was a residential PV system that was upgraded to a newer, higher performance system after 10 years of operation. Under the baseline the used modules would have been discarded and recycled using currently available techniques, resulting in a loss of high-grade materials for use in other high-tech applications. The costs and impacts from the newer PV modules are expected to be lower due to technological advancements. Additional costs for logistics and testing were assumed for the Reuse scenario. The used modules remain in use and keep producing renewable electricity for the remaining timespan in addition to the new modules and providing additional offset from the existing energy-mix (Figure 16).

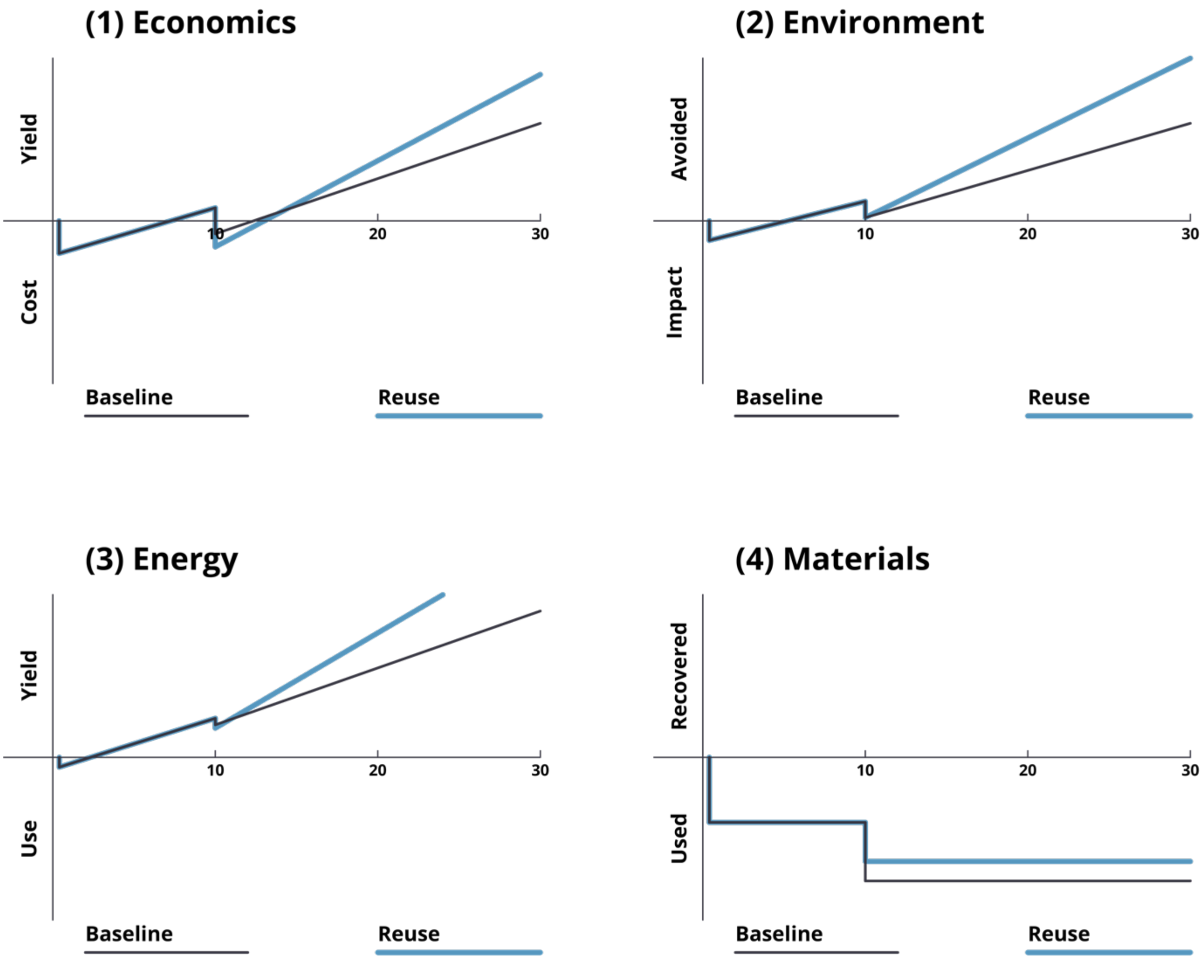

Figure 16: Impacts from a baseline upgrade scenario compared to the impacts from upgrade & Reuse

Utility System Repower & Remanufacturing

The baseline used here was a utility system that was repowered with new modules after most inverters reached the end of their lifespan after 15 years. The Remanufacturing scenario considers an alternative where the used modules are reprocessed using newer processing techniques to improve on the performance of the old modules. The result is that no new PV modules must be acquired, and only limited amounts of new materials are expected to be needed for the Remanufacturing of the used modules. Costs are also lower compared to new PV modules, as are the environmental impacts under the assumption that future disassembly methods are at least less impactful than the equivalent emissions from resource extraction and the manufacturing of new PV-grade silicon metal (Figure 17).

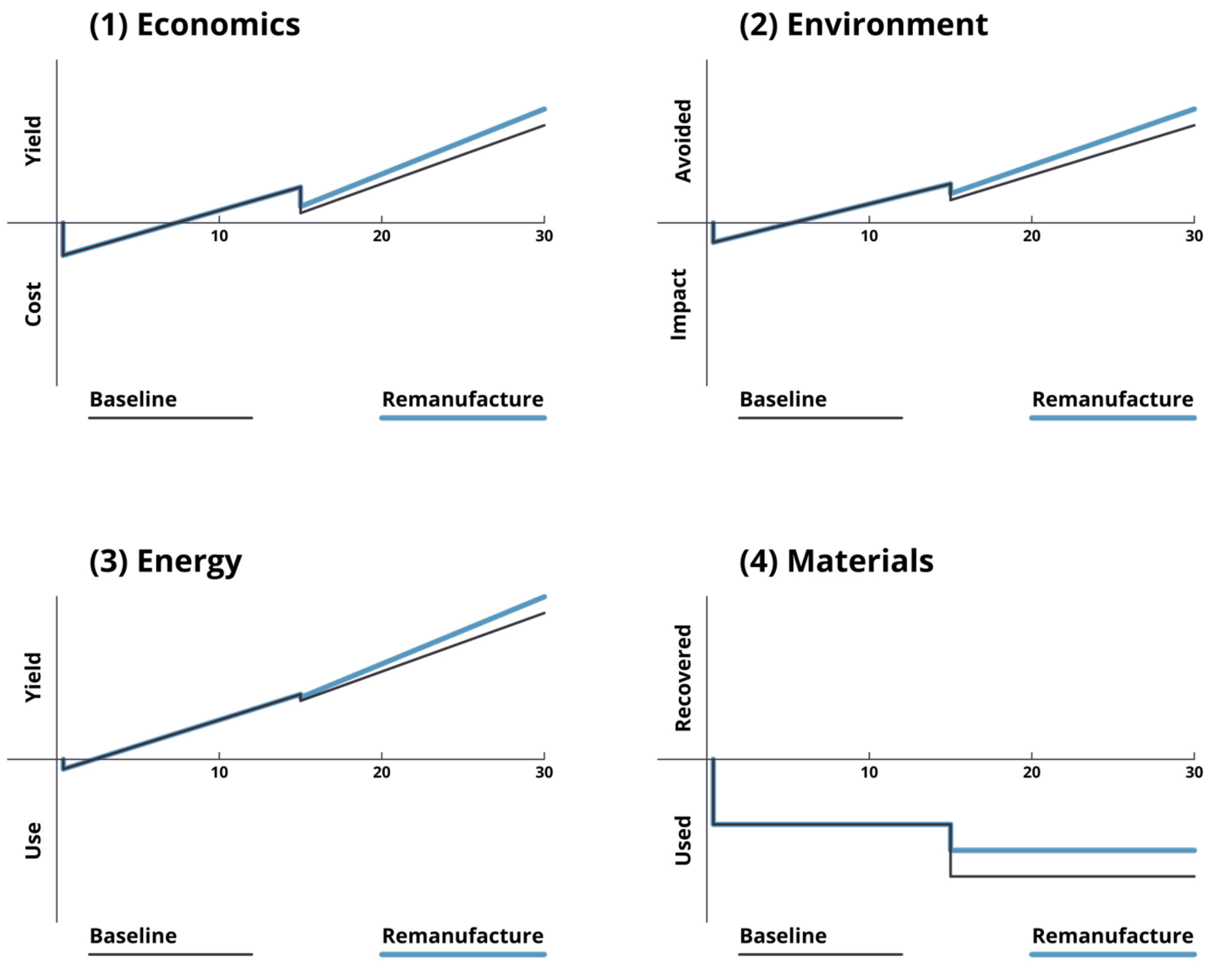

Figure 17: Impacts from a baseline repower scenario compared to the impacts from Remanufacturing

DISCUSSION

Key Findings

To summarise, the existing supply constraints and material criticality for PV are expected to worsen as demand for PV continues to grow. Even when material intensity is reducing per Wp, the growth in PV manufacturing results in a net increase in material demand. The bottleneck material differs per technology, for c-Si PV this could be silver whereas for curtain thin-film technologies this could be indium.

Recovery of these materials is insufficient since current recycling techniques are not made to recover critical- or valuable metals from EoL modules but rather to comply with EU regulation. Another contributing factor are the volumes of PV-waste, which are currently too low to justify dedicated PV recycling facilities. An intermediate alternative may therefore be to keep functional PV in use for longer and restore functionality for broken modules.

The use-phase has the largest potential for positive impact, both on environmental impacts and towards energy use and -generation. The average energy pay-back period for PV is less than 2 years, making every Wh produced after that period a net benefit to the energy-mix. However, it is still relatively common for PV modules to be replaced before their reach their technical EoL.

Costs are the primary driver for premature replacement of PV modules. Newer technologies offer better performance at a lower price, and therefore a higher yield for a given investment. Second-life PV modules must compete with these newer technologies, making it difficult to find a viable business model for extending the lifespan of existing PV modules. This is further compounded by the fact that replacement components for Repair and Refurbishment are difficult to come by, especially in small numbers.

Remanufacturing does have the potential for saving costs in manufacturing. Silicon wafers in c-Si modules represent a major share of the total module costs and manufacturing energy need. Reusing these cells could therefore be beneficial if they can be reclaimed intact and without residues from encapsulant and other materials. The processing steps required for recovery do require heat and chemicals, which detracts from the otherwise positive effects on energy use and environmental impacts. Given the potential for upgrading during a Remanufacturing process, these effects may be partly nullified depending on the performance increase achieved.

Even for PV modules that have seemingly limited purpose, due to their age or performance, repurposing them offers a potential alternative pathway that could lead to more surfaces generating electricity. They may be integrated into infrastructure, used at home on a balcony or even transported to locations with higher irradiance to maximise the remaining yield these modules can still provide. There is a case to be made for each PLE strategy, and they all come with their own set of trade-offs.

Interpretation

The PV industry has several challenges ahead, with the materials demand-supply mismatch being one of them. Since costs are one of the primary motivators for change within the PV industry, the price increase resulting from a supply-demand imbalance is likely to lead to changes in material selection, PV modules design and manufacturing, and PV use. Higher prices could result in higher demand for cheaper alternatives such as second-hand PV and for owners to keep their PV system in use for longer.

Replacement is often dictated by external factors besides costs and profits. Current subsidy structures, land-use rights and inverter lifespan all play a role in the planning of large-scale installations and their corresponding business models. Efforts towards extending the lifespan of PV modules would therefore have to be accompanied with changes to those other factors as well. Otherwise, the risk of premature replacement will remain a concern.

Provided that premature replacement continues to occur, the capacity of these modules to produce renewable electricity and offset an energy-mix with fossil fuel-based electricity generation will be lost. Once processed using current recycling methods, so will their embedded energy and carbon footprint from manufacturing, and the CRMs be lost.

PLE strategies delay these losses, but once disassembly is required to restore functionality to broken modules these strategies run into the limitations of past and current PV design. The design of these modules is optimised for a long lifespan, high efficiency, and low manufacturing costs, and not for the ease of disassembly. Meaning that PLE strategy practitioners must find creative means of taking modules apart to access internal components. Herein they receive no help from the OEM, nor do they benefit the economies of scale that manufacturers do have.

Yet the potential benefits go beyond just restoring functionality of defective modules. Remanufacturing examples show the potential for upgrading performance by combining newly developed knowledge and processing techniques to repower PV on a cell level rather than on a systems level. Although, as with other approaches, this will have to be scaled up to generate substantial impact.

Implications

The material supply-demand mismatch may endanger our efforts to successfully achieve energy transition goals and to reduce GHG emissions from electricity generations. However, PV is not the only technology that uses materials such as silver, aluminium, silicon metal and copper. The transition towards more digital technologies has the potential to reduce our energy needs, but there is an overlap in the materials needed for both transitions. This may further widen the gap between supply and demand and driving up prices for various industries.

Limitations

This study was primarily qualitative in nature and was therefore unable to add much in terms of data or otherwise quantified insights on the impacts of PLE strategies for PV. Indications were given based on the insights from literature and experts, but the range of these insights varied and were unable to offer a concrete and definitive numerical value towards the impacts of the PLE strategies.

The limited quantification can also be extended to the size of the supply-demand mismatch for CRMs and materials that may be classified as critical in the future. Higher material demand from the energy- and digital transition puts more pressure on the supply side. Simultaneously, the growth of the renewable energy- and digital technologies sectors increases their importance as part of the EU economy. This may result in more materials being eligible for the CRM label. However, the materials that would make potential CRM candidates cannot be identified from this study.

Furthermore, this study provides a snapshot of the situation at a given time. Since technology for PV continues to develop rapidly, and recycling techniques are expected to improve, the relevance of PLE strategies is expected to change over time. While offering an intermediate solution by delaying material demand, it is not sure what the long-term prospects of PLE strategies for PV may be. Contextual factors are expected to play a role as well, such as the geopolitical instability and the fluctuating price of electricity and gas. These factors have likely affected the results and findings from this study, which might limit the generalisability of the results in practical applications.

Further Research

Throughout this study, several issues were identified but not addressed or explored in detail. Their importance was noted; therefore, it is recommended that future studies address these issues.

Data Availability

Available data on system performance, lifespan, module degradation and failure rates offer insights into the overall system performance and may be used predict future performance at the time of dismantling. Often this data is not available, or not available for a given technology in each context. While modules are tested by their manufacturer, these tests cannot account for various real-world conditions. Having this data available from existing installations could help with, among others, the development of business models for Reuse and to determine the economic viability of other PLE strategies.

Module Design Standardisation

Standardised designs with common sizes for frames and cells used, may offer opportunities for the exchange of components between modules from different manufacturers. This could be beneficial to PLE strategies and the cost of manufacturing but may affect improvements in efficiency that require a change of form-factor. The exact impact this may have and what complexities may arise from increased module standardisation should be further explored.

Component Recovery Trade-Offs

The choice between one component over another is a trade-off that must in some cases be made towards its recovery. In c-Si PV modules, the choice appears to be between recovering the silicon cell or the PV glass containing antimony. One approach may recover more embedded energy and avoid the need for new wafers to be manufactured, whereas the other approach may prevent toxic antimony from being used in insulation or other construction materials. The effects of such a trade-off, and whether such a trade-off might be necessary in the future, are areas for further studies to explore.

Consumer Attitude

Literature and interviews showed the importance of attitude towards second-life PV as an important factor in acceptance and adoption rate. Studies have shown that regardless of this importance, very little research was done on the specific aspects in consumer attitude that affected the decision-making for new of second-life PV. Similarly, the reasons for early retirement of a PV system, specifically for residential use, were only found in one study specific for Tokyo. Further studies could address the underlaying reasons for premature replacement or discarding for either a more generalisable context or specific to the EU market, to draw conclusions on replacement behaviour and to help quantify the stream of discarded PV modules.

Human Rights

This study briefly touched upon the leverage of some countries over the supply of certain materials and their human rights record. The inclusion of such factors in PV procurement could send signals advocating for improvements. The exact means of measuring and communicating these conditions require further research.

Standardisation and Technological Lock-in

Having a standardised manufacturing process and long-term availability of spare parts would benefit a circular PV industry. However, to maximise the benefits from using standardised part and designs, it may be beneficial to manufacture one technology for a much longer timespan of, e.g., 50+ years. This results in a trade-off between manufacturing one design for a long period of time and continuing to improve efficiency by changing various aspects to the construction and processing methods. Locking in one technology and optimising it over the long-term could result in costs savings, material use reduction whilst remaining compatible with earlier iterations allowing for the exchange of parts and slight upgrades over time. The traditional approach of striving for maximum efficiency may lead to higher performance modules after 50 years but could apply further pressure on the materials supply. Further research would be needed to find the potential benefits to such an approach.

CONCLUSIONS

This study aimed to address the impact of PLE strategies for PV on a growing renewable energies system. The findings conclude that all PLE strategies described provide a positive impact on environmental aspects, material demand, and energy use and production. Extending the lifespan of existing PV maintains installed capacity, requiring fewer new products to replace otherwise lost capacity. This helps delay the increase in demand for new resources and buys time to address challenges in materials recovery and PV module design.

It also has indirect impacts by showcasing the benefits of circular approaches to technically complex products that utilise CRMs and valuable materials to operate. PLE strategies are a tangible example of possible alternatives and help an otherwise abstract concept of a Circular Economy be more concrete and easier to understand. It portrays the inherent value of what we already have and provides potential pathways on how to do even more with it.

Research Process

This research project was characterised by a long pre-research phase to find and properly define a knowledge gap for three pillars: CRMs, Circular Economy, and the energy transition. It showed the complexity of this wicked problem and the extent of background knowledge needed to understand it well enough to find concrete gaps or limitations to current approaches.

The literature review approached the critical materials supply-demand challenges from a CE perspective. While this led to findings on the potential impacts from PLE strategies, it may have steered the research towards a CE solution right from the start. Alternative perspectives and approaches were therefore not taken into consideration. A concrete example of a decision that affected the outcome was to not include Repurpose in the literature review. The definition of Repurpose as Reuse in a different use-context was deemed not applicable to the case of PV. Later research did provide insights on the potential relevance of applying PV in unconventional ways, but it could have been part of the overall focus from the beginning.

The case study was limited by the number of examples of PLE strategy applications. For the identified cases this study could have gone more in depth by gathering more data and insights on the module acquisition, procedures used and quantifiable results. Given the choice for a mixed method approach, the time available for each method was limited and trade-offs had to be made.

These trade-offs also affected the expert interviews. The interviews were kept relatively short, focussed on several key discussion points, and were summarised. By allocating more time to the interviews, more experts from various backgrounds could have been interviewed. In that case, all the interviews themselves could have been transcribed and coded as opposed to only one to show the common insights and disagreements on PLE approaches.

Insights from literature, case study and expert interviews were used to develop a concept PV PLE Framework. Several iterations and revisions, based on feedback from experts, led to the final concept version. However, the pathways as presented were not tested in practise and depend on disassembly technology to develop to a point where Repair, Refurbishment and Remanufacturing can be performed easily and cost effectively. For now, it provides a series of options and criteria that could be considered.

Each pathway has its own benefits and drawbacks from the perspectives of economics, environmental impacts, energy use and production, and materials demand and recovery. Some of these benefits, for two common replacement scenarios were visualised. However, these visualisations were merely intended to indicate the potential rather than to quantify or prove the effects in those scenarios. These scenarios could have been developed further and improved through iteration and multiple rounds of expert feedback.

Recommendations for Follow-up Studies

Several of the issues addressed in this study could be used as a starting point for follow-up studies. These studies could expand upon a concept and further substantiate it by adding data or by developing a next iteration that could be applied to a practical use-case. One example is to test the Concept PV PLE Framework in practise to learn whether the criteria as chosen are accurate and whether the pathways can be achieved.

Another example are the indicative scenarios. These may be further developed by quantifying the impacts each PLE strategy could have for common replacement scenarios. These may include cases for residential upgrades as well as for utility-scale PV farm repowering. The application of one or multiple PLE strategies should be quantified to find the specific contexts for which these strategies do or do not work.

Lastly, the qualitative knowledge provided by PV experts could be enhanced by expanding the backgrounds of the interviewees and by applying transcription and coding methods to all interview results. This has the potential to compare insights between experts of various background more easily and to find patterns specific to, e.g., researchers, policy makers, industry, investors, etc.

Scientific Contribution

This study has shown that there is a potential for PLE strategies for PV in addressing the supply-demand challenges for CRMs. These strategies were found to offer beneficial impacts to several key aspects including environmental, energy and materials. It also showed several challenges that will need to be addressed in the future if PLE strategies are to be a part of a circular implementation of PV technologies. Several key limitations to PLE strategies were found, pointing towards both the limitations of these strategies currently and to possibilities for design improvements of PV modules that could improve their circularity potential. These may indicate further gaps in scientific knowledge that could be addressed in future studies.

RECOMMENDATIONS

Based on the findings from this study, several interventions and actions are recommended for three groups of actors: researchers, industry players and policy makers.

Researchers

Shift in R&D Focus

The primary focus areas for PV R&D have been to improve efficiency and to lower manufacturing costs. This has contributed to the rapid growth of installed PV capacity; however, it remained in line with linear economy thinking and is in part responsible for resource- and waste challenges. A shift is needed towards thinking in multiple life cycles, preserving existing value and the recovery of all components and materials at EoL. This includes aspects such as material selection, module construction Repairability, modularity and standardisation for new PV modules. Regarding the stock of existing PV, new ways of disassembly are needed to facilitate Repair, Refurbishment and Remanufacturing. Both approaches are needed since current design dictated the circularity of future PV and existing PV may offer a valuable source of raw materials to power our energy- and digital transitions.

Upgrade Potential for Current PV

Newer technologies and processing improvements have led to improvements in electricity generation efficiency. This knowledge and ability may be utilised to upgrade the performance of older PV modules and cells. One example has already shown the potential for using newer processing techniques to improve efficiency. Other approaches that use c-Si cells from used modules to achieve higher performance should be explored. Another added benefit is that such an approach avoids the energy and processing needed to remelt the silicon metal and to manufacture new cells.

Industry

Module Design & Construction

Current PV module design is meant to last for several decades in harsh outdoor conditions. The laminated construction offers this degree of long-term reliability but makes any attempt at disassembly and component Repair difficult if not impossible without damaging other parts. Taking a more modular approach or by using only an edge-seal could significantly affect the ease of disassembly for Repair, Refurbishment or Remanufacturing. This could even benefit the PV manufacturer themselves, as these types of modules could serve as a future resource supply and as feedstock for future module upgrades.

Scale-up of PLE Approaches

Aside from manufacturing PV modules, a new industry is required to deal with unwanted or non-functional PV modules. Scaling up techniques for Repair, Refurbishment and Remanufacturing of used PV progresses the understanding of these processes and offers the benefits of economies of scale. This should be timed with the available volume of discarded PV and coordinated geographically to serve a local market. That way the incoming volume could ensure continuous operation and the distance to an installation could reduce the costs and impacts from logistics.

Transparency on Materials

Knowing exactly what materials and in what quantities were used to manufacture a specific PV module offers valuable insights that may be used to evaluate the viability of a given PLE strategy and towards the EoL material recovery. Nowadays this information is not available on a per-module-basis as manufacturers prefer to keep such information secret. However, given the rapid rate of development and the inability for most manufacturers to keep this information secret once a product has reached the market, there are few reasons why this information should not be made public after a given time. Modules could be given an QR-code (Quick Response) or an RFID-tag (Radio-Frequency Identification) that links to an online database with the Bill of Materials (BOM). Such as database could be made to publish this data after a set amount of time, e.g., 5 or 10 years. By that time there would be no competitive reason for keeping it secret.

Policy Makers

Plan for the Long-Term

A circular PV system would have to account for multiple PV life cycles. With the current life expectancy of ± 25-30 years, it takes just four complete life cycles to reach 100 years. Planning for such as system requires policies and regulatory frameworks that are designed to last for at least as long. Policy makers should therefore start considering what is needed to support and promote circular implementations of PV. This means planning beyond the lifespan of the average human and well beyond the timeframe of a sitting government. Such plans should consider subsidies, lang-use rights, minimal module lifespan, OEM participation, EoL processing, etc.

Consider Side-Effects

Most legislation promoting the use of renewable energy systems are created with the best intentions. However, there are cases where rules and requirements result in unwanted side-effects. One example, as discussed in this study, is the compliance with BENG-requirements for renewable generation on new developments. Findings from Marktplaats offerings showed advertisements for small numbers of relatively new, high-capacity PV modules. There will likely always be parties that aim to find loopholes or abuse the system, but this should be made as difficult as possible to achieve the intended result rather than any unintended side-effects.

Make Recovery Requirements More Specific

Current recycling requirements intend to achieve a recycling rate based on a mass percentage. Results from literature and interviews pointed out that this approach has led to downcycling of materials. For a CE to succeed, the value of components and materials must be maintained. Therefore, policy should reflect this CE focus by requiring recyclers to recover those materials that are critical, valuable, and essential to EU industry and the energy- and digital transitions.

REFERENCES

≥ *Vind zonnepanelen | Zo goed als nieuw in Zonnepanelen en Toebehoren op Marktplaats*. (n.d.). Retrieved 25 July 2022, from https://www.marktplaats.nl/l/doe-het-zelf-en-verbouw/zonnepanelen-en-toebehoren/f/paneel/3383/#q:zonnepanelen|f:31,32,3382|searchInTitleAndDescription:true

2nd International Conference on Green Building, Materials and Civil Engineering, GBMCE 2013 (Vols 368–370, Issue 1). (2013). Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84885770231&partnerID=40&md5=a5863933b25aee9d175bb0f819cfb185

2016 Electronics Goes Green 2016+, EGG 2016. (2017). 2016 Electronics Goes Green 2016+, EGG 2016. Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85013813573&partnerID=40&md5=a97233b677d9e5a52fe3ab772f5d1cc7

Abokersh, M. H., Norouzi, M., Boer, D., Cabeza, L. F., Casa, G., Prieto, C., Jiménez, L., & Vallès, M. (2021). A framework for sustainable evaluation of thermal energy storage in circular economy. *Renewable Energy*, *175*, 686–701. Scopus. https://doi.org/10.1016/j.renene.2021.04.136

Amato, A., & Beolchini, F. (2019). End-of-life CIGS photovoltaic panel: A source of secondary indium and gallium. *Progress in Photovoltaics: Research and Applications*, *27*(3), 229–236. Scopus. https://doi.org/10.1002/pip.3082

Ansanelli, G., Fiorentino, G., Tammaro, M., & Zucaro, A. (2021). A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels. *Applied Energy*, *290*. Scopus. https://doi.org/10.1016/j.apenergy.2021.116727

Ashby, M. (2015). *Materials and sustainable development* (1st edition). Elsevier.

Benda, V., & Černá, L. (2020). PV cells and modules–State of the art, limits and trends. *Heliyon*, *6*(12), e05666.

Bertino, G., Menconi, F., Zraunig, A., Terzidis, E., & Kisser, J. (2019). *Innovative circular solutions and services for new buildings and refurbishments*. *183*, 83–91. Scopus. https://doi.org/10.2495/ARC180081

Blagoeva, D. T., & Pavel, C. C. (2017). *Materials impact on the EU's competitiveness of the renewable energy, storage and e-mobility sectors: Wind power, solar photovoltaic and battery technologies*. Publications Office of the European Union.

Bobba, S., Mathieux, F., Ardente, F., Blengini, G. A., Cusenza, M. A., Podias, A., & Pfrang, A. (2018). Life Cycle Assessment of repurposed electric vehicle batteries: An adapted method based on modelling energy flows. *Journal of Energy Storage*, *19*, 213–225. Scopus. https://doi.org/10.1016/j.est.2018.07.008

Boldz. (n.d.). *Boldz | Powerbank, de SolarTable met Karakter*. Retrieved 12 July 2022, from https://boldz.one/

Bombach, E., Röver, I., Müller, A., Schlenker, S., Wambach, K., Kopecek, R., & Wefringhaus, E. (2006). Technical experience during thermal and chemical recycling of a 23 year old PV generator formerly installed on Pellworm island. *21st European Photovoltaic Solar Energy Conference*, 4–8.

Brenner, W., & Adamovic, N. (2020). *Creating sustainable solutions for photovoltaics*. 1777–1782. Scopus. https://doi.org/10.23919/MIPRO48935.2020.9245369

CBS. (2021, September 30). *Hernieuwbare Energie in Nederland 2020—5. Zonne-energie* [Webpagina]. Centraal Bureau voor de Statistiek. https://www.cbs.nl/nl-nl/longread/aanvullende-statistische-diensten/2021/hernieuwbare-energie-in-nederland-2020/5-zonne-energie

CBS. (2022, June 16). *StatLine—Hernieuwbare elektriciteit; productie en vermogen*. https://opendata.cbs.nl/#/CBS/nl/dataset/82610NED/table?ts=1667218094554

Charles, R. G., Davies, M. L., & Douglas, P. (2017). *Third generation photovoltaics-Early intervention for circular economy and a sustainable future*. 2016 Electronics Goes Green 2016+, EGG 2016. Scopus. https://doi.org/10.1109/EGG.2016.7829820

Charles, R. G., Davies, M. L., Douglas, P., Hallin, I. L., & Mabbett, I. (2019). Sustainable energy storage for solar home systems in rural Sub-Saharan Africa – A comparative examination of lifecycle aspects of battery technologies for circular economy, with emphasis on the South African context. *Energy*, *166*, 1207–1215. Scopus. https://doi.org/10.1016/j.energy.2018.10.053

Chazarra-Zapata, J., Molina-Martínez, J. M., De La Cruz, F.-J. P., Parras-Burgos, D., & Canales, A. R. (2020). How to reduce the carbon footprint of an irrigation community in the south-east of Spain by use of solar energy. *Energies*, *13*(11). Scopus. https://doi.org/10.3390/en13112848

Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, *27*. Scopus. https://doi.org/10.1016/j.esr.2019.100431

Clean Tech Regio. (2022, August 9). *Weeshuis voor Zonnepanelen levert panelen aan Oekraïne—Cleantech Regio*. WEESHUIS VOOR ZONNEPANELEN LEVERT PANELEN AAN OEKRAÏNE. https://www.cleantechregio.nl/nieuws/1838-weeshuis-voor-zonnepanelen-levert-panelen-aan-oekraine

Contreras-Lisperguer, R., Muñoz-Cerón, E., Aguilera, J., & de la Casa, J. (2021). A set of principles for applying Circular Economy to the PV industry: Modeling a closed-loop material cycle system for crystalline photovoltaic panels. *Sustainable Production and Consumption*, *28*, 164–179. Scopus. https://doi.org/10.1016/j.spc.2021.03.033

Cusenza, M. A., Guarino, F., Longo, S., Mistretta, M., & Cellura, M. (2019). Reuse of electric vehicle batteries in buildings: An integrated load match analysis and life cycle assessment approach. *Energy and Buildings*, *186*, 339–354. Scopus. https://doi.org/10.1016/j.enbuild.2019.01.032

Daljit Singh, J. K., Molinari, G., Bui, J., Soltani, B., Rajarathnam, G. P., & Abbas, A. (2021). Life cycle analysis of disposed and recycled end-of-life photovoltaic panels in australia. *Sustainability (Switzerland)*, *13*(19). Scopus. https://doi.org/10.3390/su131911025

De Ceuvel. (n.d.-a). Algemene Informatie. *Algemene Informatie*. Retrieved 20 November 2022, from https://deceuvel.nl/nl/about/general-information/

De Ceuvel. (n.d.-b). Zonnepanelen. *Zonnepanelen*. Retrieved 20 November 2022, from https://deceuvel.nl/nl/about/sustainable-technology/solar-energy/

de Oliveira, M. C. C., Cassini, D. A., Diniz, A. S. A. C., Soares, L. G., Viana, M. M., Kazmerski, L. L., & Lins, V. D. F. C. (2019). Comparison and analysis of performance and degradation differences of crystalline-Si photovoltaic modules after 15-years of field operation. *Solar Energy*, *191*, 235–250. Scopus. https://doi.org/10.1016/j.solener.2019.08.051

Deng, R., Chang, N., Lunardi, M. M., Dias, P., Bilbao, J., Ji, J., & Chong, C. M. (2021). Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis. *Progress in Photovoltaics: Research and Applications*, *29*(7), 760–774.

Dominguez, S., Laso, J., Margallo, M., Aldaco, R., Rivero, M. J., Irabien, Á., & Ortiz, I. (2018). LCA of greywater management within a water circular economy restorative thinking framework. *Science of the Total Environment*, *621*, 1047–1056. Scopus. https://doi.org/10.1016/j.scitotenv.2017.10.122

EC. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, WEEE. *Official Journal of the European Union L*, *197*, 38–71.

Einhaus, R., Madon, F., Degoulange, J., Wambach, K., Denafas, J., Lorenzo, F. R., Abalde, S. C., Garcia, T. D., & Bollar, A. (2018). *Recycling and Reuse potential of NICE PV-Modules*. 561–564. Scopus. https://doi.org/10.1109/PVSC.2018.8548307

Ellen MacArthur Foundation. (n.d.-a). *Circulate products and materials*. Retrieved 18 November 2022, from https://ellenmacarthurfoundation.org/circulate-products-and-materials

Ellen MacArthur Foundation. (n.d.-b). *Eliminate waste and pollution*. Retrieved 18 November 2022, from https://ellenmacarthurfoundation.org/eliminate-waste-and-pollution

Ellen MacArthur Foundation. (n.d.-c). *Regenerate nature*. Retrieved 18 November 2022, from https://ellenmacarthurfoundation.org/regenerate-nature

Erol, I., Peker, I., Turan, İ., & Benli, T. (2022). Closing the Loop in Photovoltaic Solar and Wind Power Supply Chains: An investigation in Turkey through Neutrosphopic-DELPHI-based Force Field Analysis and Neutrosphopic-DEMATEL. *Sustainable Energy Technologies and Assessments*, *52*. Scopus. https://doi.org/10.1016/j.seta.2022.102292

EU. (2012). *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)*. Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0019

European Commission. (n.d.). *Conflict Minerals Regulation: The regulation explained*. Retrieved 20 November 2022, from https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation/regulation-explained_en

European Commission. (2017). *Methodology for establishing the EU list of critical raw materials: Guidelines.* Publications Office. https://data.europa.eu/doi/10.2873/769526

European Commission. (2020). *Study on the EU's list of critical raw materials (2020): Final Report*. Publications Office. https://doi.org/10.2873/11619

European Commission. (2022). *REPowerEU Plan*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0230&from=EN

Eurostat. (2022). *Share of energy from renewable sources | Eurostat* [Database]. Share of Energy from Renewable Sources. https://ec.europa.eu/eurostat/databrowser/view/NRG_IND_REN__custom_2276454/default/table?lang=en

Fair Solar Netwerk. (n.d.). *Ons Netwerk*. Fair solar netwerk. Retrieved 14 November 2022, from https://fairsolarnetwerk.nl/netwerk/

Franco, M. A., & Groesser, S. N. (2021). A systematic literature review of the solar photovoltaic value chain for a circular economy. *Sustainability (Switzerland)*, *13*(17). Scopus. https://doi.org/10.3390/su13179615

Fraunhofer ISE. (2021). *PHOTOVOLTAICS REPORT* (FHG-SK: ISE-PUBLIC). Fraunhofer Institute. 27 July 2021

Gautam, A., Shankar, R., & Vrat, P. (2022). Managing end-of-life solar photovoltaic e-waste in India: A circular economy approach. *Journal of Business Research*, *142*, 287–300. Scopus. https://doi.org/10.1016/j.jbusres.2021.12.034

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. Scopus. https://doi.org/10.1016/j.jclepro.2015.09.007

Gielen, D. (2021). Critical minerals for the energy transition. *International Renewable Energy Agency: Abu Dhabi.*

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38–50. Scopus. https://doi.org/10.1016/j.esr.2019.01.006

Glatthaar, J., Kamdje, E., Ricklefs, U., Stadlbauer, E. A., Glatthaar, J., Kamdje, E., Barnickel, J. B., Dax, M., Schaub, V., & Stevens, H. G. (2017). Development of a Modular Cradle to Cradle Process-Chain for c-Si-PV Panel Recycling. *Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands*, 25–29.

Gregoir, L., & Van Acker, K. (2022). Metals for Clean Energy: Pathways to solving Europe's raw materials challenge. *Eurometaux, KU Leuven*.

Guerin, T. F. (2020a). Assessing Technical Options for Handling Packaging Wastes from Construction of a Solar PV Powerstation: A Case Study from a Remote Site. *Water, Air, and Soil Pollution*, *231*(5). Scopus. https://doi.org/10.1007/s11270-020-04604-z

Guerin, T. F. (2020b). Evaluating treatment pathways for managing packaging materials from construction of a solar photovoltaic power station. *Waste Management and Research*, *38*(12), 1345–1357. Scopus. https://doi.org/10.1177/0734242X20939627

Heath, G. A., Silverman, T. J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., & Wade, A. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nature Energy*, *5*(7), 502–510. Scopus. https://doi.org/10.1038/s41560-020-0645-2

Hof, M., Steenmeijer, M., Kuppevelt, M. van, Bruggen, A. van, & Quik, J. (2022). *Veilige en duurzame zonnepanelen: Tijdens ontwerp aandacht nodig voor milieu-impact* (p. 20). RIVM. https://www.rivm.nl/sites/default/files/2022-10/DIRECT%20Veilige%20en%20duurzame%20zonnepanelen.pdf

Holland Solar. (n.d.). *Holland Solar—Leden*. Retrieved 19 October 2022, from https://hollandsolar.nl/leden?marktsegment=0--1-zonnestroom

Hsu, C.-H., & Lin, C.-C. (2019). *Recycling New Energy—Discussion on the Application of Zero Waste to Taiwan Animal Husbandry*. *117*. Scopus. https://doi.org/10.1051/e3sconf/201911700017

Husgafvel, R., Linkosalmi, L., Sakaguchi, D., & Hughes, M. (2021). How to advance sustainable and circular economy-oriented public procurement-A review of the operational environment and a case study from the Kymenlaakso region in Finland. In *Circular Economy and Sustainability: Volume 1: Management and Policy* (pp. 227–277). Scopus. https://doi.org/10.1016/B978-0-12-819817-9.00015-6

IEA. (2020). *Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals*. IEA. https://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-critical-minerals

IEA. (2021). *Key World Energy Statistics 2021*. OECD. https://doi.org/10.1787/2ef8cebc-en

IEA. (2022). The Role of Critical Minerals in Clean Energy Transitions. In *World Energy Outlook Special Report*. International Energy Agency Paris, France.

IPCC. (2014). *Climate change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*. IPCC.

IRENA. (2019a). *A New World: The Geopolitics of the Energy Transformation*. IRENA. http://geopoliticsofrenewables.org/assets/geopolitics/Reports/wp-content/uploads/2019/01/Global_commission_renewable_energy_2019.pdf

IRENA. (2019b). *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: Paper)*. International Renewable Energy Agency.

Iturrondobeitia, M., Akizu-Gardoki, O., Amondarain, O., Minguez, R., & Lizundia, E. (2022). Environmental Impacts of Aqueous Zinc Ion Batteries Based on Life Cycle Assessment. *Advanced Sustainable Systems*, *6*(1). Scopus. https://doi.org/10.1002/adsu.202100308

Jordan, D. C., Kurtz, S. R., VanSant, K., & Newmiller, J. (2016). Compendium of photovoltaic degradation rates. *Progress in Photovoltaics: Research and Applications*, *24*(7), 978–989. Scopus. https://doi.org/10.1002/pip.2744

Kim, H., & Park, H. (2018). PV waste management at the crossroads of circular economy and energy transition: The case of South Korea. *Sustainability (Switzerland)*, *10*(10). Scopus. https://doi.org/10.3390/su10103565

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37–46. Scopus. https://doi.org/10.1016/j.ecolecon.2017.06.041

Lameh, M., Abbas, A., Azizi, F., & Zeaiter, J. (2021). A simulation-based analysis for the performance of thermal solar energy for pyrolysis applications. *International Journal of Energy Research*, *45*(10), 15022–15035. Scopus. https://doi.org/10.1002/er.6781

Lee, J.-K., Lee, J.-S., Ahn, Y.-S., Kang, G.-H., Song, H.-E., Kang, M.-G., Kim, Y.-H., & Cho, C.-H. (2018). Simple pretreatment processes for successful reclamation and remanufacturing of crystalline silicon solar cells. *Progress in Photovoltaics: Research and Applications*, *26*(3), 179–187. Scopus. https://doi.org/10.1002/pip.2963

Maceno, M. M. C., Pilz, T. L., & Oliveira, D. R. (2022). Life Cycle Assessment and Circular Economy: A Case Study of a Photovoltaic Solar Panel in Brazil. *Journal of Environmental Accounting and Management*, *10*(1), 91–111. Scopus. https://doi.org/10.5890/JEAM.2022.03.008

Mahmoudi, S., Huda, N., & Behnia, M. (2020). Environmental impacts and economic feasibility of end of life photovoltaic panels in Australia: A comprehensive assessment. *Journal of Cleaner Production*, *260*. Scopus. https://doi.org/10.1016/j.jclepro.2020.120996

Marktplaats. (n.d.). *Marktplaats—Help & Info*. Over Marktplaats. Retrieved 20 November 2022, from https://www.marktplaats.nl/i/help/over-marktplaats/index.dot.html

Mendoza, J. M. F., Gallego-Schmid, A., Schmidt Rivera, X. C., Rieradevall, J., & Azapagic, A. (2019). Sustainability assessment of home-made solar cookers for use in developed countries. *Science of the Total Environment*, *648*, 184–196. Scopus. https://doi.org/10.1016/j.scitotenv.2018.08.125

Miettunen, K., & Santasalo-Aarnio, A. (2021). Eco-design for dye solar cells: From hazardous waste to profitable recovery. *Journal of Cleaner Production*, *320*. Scopus. https://doi.org/10.1016/j.jclepro.2021.128743

Ministerie van Algemene Zaken. (2022). *Duurzame energie—Rijksoverheid.nl* [Onderwerp]. Ministerie van Algemene Zaken. https://www.rijksoverheid.nl/onderwerpen/duurzame-energie

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2019, December 24). *Besluit van 13 december 2019, houdende wijziging van het Bouwbesluit 2012 en van enkele andere besluiten inzake bijna energie-neutrale nieuwbouw* [Officiële publicatie]. Artikelen 2 en 120 van de Woningwet, 2.4 van de Crisis- en herstelwet en 4.3, eerste lid, en 5.1 van de Omgevingswet en artikel 9 van de richtlijn 2010/31/EU van het Europees Parlement en de Raad van 19 mei 2010 betreffende de energieprestatie van gebouwen (herschikking) (PbEU L153/13); Ministerie van Justitie en Veiligheid. https://zoek.officielebekendmakingen.nl/stb-2019-501.html#extrainformatie

Motta, C. M., Cerciello, R., De Bonis, S., Mazzella, V., Cirino, P., Panzuto, R., Ciaravolo, M., Simoniello, P., Toscanesi, M., & Trifuoggi, M. (2016). Potential toxicity of improperly discarded exhausted photovoltaic cells. *Environmental Pollution*, *216*, 786–792.

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M., & Scapolo, F. (2022). *Towards a green & digital future: Key requirements for successful twin transitions in the European Union*. Publications Office of the European Union.

Murakami, S., Yamamoto, H., & Toyota, T. (2021). Potential impact of consumer intention on generation of waste photovoltaic panels: A case study for tokyo. *Sustainability (Switzerland)*, *13*(19). Scopus. https://doi.org/10.3390/su131910507

Nakakura, M., Matsubara, K., Bellan, S., & Kodama, T. (2019). *Direct Simulation of Volumetric Solar Receiver with Highly Concentrated Radiation*. *556*(1). Scopus. https://doi.org/10.1088/1757-899X/556/1/012060

Nationaal (W)EEE Register. (2018). *Rapportage over 2017*.

Nationaal (W)EEE Register. (2019). *Rapportage over 2018*.

Nationaal (W)EEE Register. (2020). *Rapportage 2019*.

Nationaal (W)EEE Register. (2021). *Rapportage 2020*.

Nationaal (W)EEE Register. (2022). *Rapportage 2021*.

Obrecht, M., Singh, R., & Zorman, T. (2022). Conceptualizing a new circular economy feature – storing renewable electricity in batteries beyond EV end-of-life: The case of Slovenia. *International Journal of Productivity and Performance Management*, *71*(3), 896–911. Scopus. https://doi.org/10.1108/IJPPM-01-2021-0029

Oteng, D., Zuo, J., & Sharifi, E. (2021). A scientometric review of trends in solar photovoltaic waste management research. *Solar Energy*, *224*, 545–562.

Ovaitt, S., Mirletz, H. M., Hegedus, A., Gaulding, A., & Barnes, T. (2021). *PV Evolution in the light of Circular Economy*. 1570–1575. Scopus. https://doi.org/10.1109/PVSC43889.2021.9518683

Palitzsch, W. (2018). *Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications—Latest News from CABRISS (EU Collaborative Project)*. 2462–2464. Scopus. https://doi.org/10.1109/PVSC.2018.8548168

Palitzsch, W., Killenberg, A., Schonherr, P., & Loser, U. (2018). *Photovoltaic Recycling with the help of Water and Light—It does not get greener*. 2465–2466. Scopus. https://doi.org/10.1109/PVSC.2018.8548095

Park, J., Kim, W., Cho, N., Lee, H., & Park, N. (2016). An eco-friendly method for reclaimed silicon wafers from a photovoltaic module: From separation to cell fabrication. *Green Chemistry*, *18*(6), 1706–1714. Scopus. https://doi.org/10.1039/c5gc01819f

Potting, J., Hanemaaijer, A., Delahaye, R., Ganzevles, J., Hoekstra, R., & Lijzen, J. (2018). *Circular Economy: What we want to know and can measure. Framework and baseline assessment for monitoring the progress of the circular economy in the Netherlands* (No. 3217). PBL.

Rahmani, B., Rio, M., Lembeye, Y., & Crebier, J.-C. (2022). *Design for Reuse: Residual value monitoring of power electronics' components*. *109*, 140–145. Scopus. https://doi.org/10.1016/j.procir.2022.05.227

Rijkswaterstaat. (2021, February 16). *Kennisgeving van het algemeen verbindend verklaren van de overeenkomst inzake de afvalbeheerbijdrage voor AEEA, Ministerie van Infrastructuur en Waterstaat* [Officiële publicatie]. Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. https://zoek.officielebekendmakingen.nl/stcrt-2021-7385.html

Salim, H., Stewart, R. A., Sahin, O., Sagstad, B., & Dudley, M. (2021). R3SOLVE: A serious game to support end-of-life rooftop solar panel waste management. *Sustainability (Switzerland)*, *13*(22). Scopus. https://doi.org/10.3390/su132212418

Schoden, F., Detzmeier, J., Schnatmann, A. K., Blachowicz, T., & Schwenzfeier-Hellkamp, E. (2022). Investigating the Remanufacturing Potential of Dye-Sensitized Solar Cells. *Sustainability (Switzerland)*, *14*(9). Scopus. https://doi.org/10.3390/su14095670

Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J., & Lauwigi, C. (2012). Raw material consumption of the European Union—Concept, calculation method, and results. *Environmental Science and Technology*, *46*(16), 8903–8909. Scopus. https://doi.org/10.1021/es300434c

Sharma, P., & Goyal, P. (2020). Evolution of PV technology from conventional to nano-materials. *Materials Today: Proceedings*, *28*, 1593–1597.

Smith, Y. R., & Bogust, P. (2018). Review of solar silicon recycling. *TMS Annual Meeting & Exhibition*, 463–470.

Sungevity. (n.d.). *DE SCHADUWKANT VAN ZONNEPANELEN* [Whitepaper]. https://www.sungevity.nl/wp-content/uploads/2021/02/impactreport-2020.pdf

Takada, T., Uchiyama, T., Okada-Shudo, Y., Hoshino, K., Koizumi, K., Takeoka, Y., & Vohra, V. (2020). High Performance Organic Solar Cells Fabricated Using Recycled Transparent Conductive Substrates. *ACS Sustainable Chemistry and Engineering*, *8*(14), 5807–5814. Scopus. https://doi.org/10.1021/acssuschemeng.0c01966

Tan, V., Dias, P. R., Chang, N., & Deng, R. (2022). Estimating the Lifetime of Solar Photovoltaic Modules in Australia. *Sustainability (Switzerland)*, *14*(9). Scopus. https://doi.org/10.3390/su14095336

Tao, J., & Yu, S. (2015). Review on feasible recycling pathways and technologies of solar photovoltaic modules. *Solar Energy Materials and Solar Cells*, *141*, 108–124. Scopus. https://doi.org/10.1016/j.solmat.2015.05.005

Theelen, M., Kester, J., Hauck, M., Späth, M., Kuypers, A., & Sinke, W. (2021). *Tijd voor duurzame zonne-energie: Zonnestroom van hernieuwbaar naar duurzaam*. https://publications.tno.nl/publication/34638904/Mnc8mC/TNO-2021-tijd.pdf

Tsanakas, J. A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J., & Voroshazi, E. (2020). Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. *Progress in Photovoltaics: Research and Applications*, *28*(6), 454–464. Scopus. https://doi.org/10.1002/pip.3193

Uggetti, E., García, J., Álvarez, J. A., & García-Galán, M. J. (2018). Start-up of a microalgae-based treatment system within the biorefinery concept: From wastewater to bioproducts. *Water Science and Technology*, *78*(1), 114–124.

USGS. (2021). Mineral commodity summaries. *US Geological Survey: Reston, VA, USA*, *200*.

van der Roest, E., van der Spek, M., Ramirez, A., van der Zwaan, B., & Rothenberg, G. (2017). Converting Waste Toilet Paper into Electricity: A First-Stage Technoeconomic Feasibility Study. *Energy Technology*, *5*(12), 2189–2197. Scopus. https://doi.org/10.1002/ente.201700247

Walzberg, J., Carpenter, A., & Heath, G. A. (2021). Role of the social factors in success of solar photovoltaic reuse and recycle programmes. *Nature Energy*, *6*(9), 913–924. Scopus. https://doi.org/10.1038/s41560-021-00888-5

Wat we doen | Boldz. (n.d.). Retrieved 19 October 2022, from https://boldz.one/wat-we-doen/

Wilson, G. M., Al-Jassim, M., Metzger, W. K., Glunz, S. W., Verlinden, P., Xiong, G., Mansfield, L. M., Stanbery, B. J., Zhu, K., Yan, Y., Berry, J. J., Ptak, A. J., Dimroth, F., Kayes, B. M., Tamboli, A. C., Peibst, R., Catchpole, K., Reese, M. O., Klinga, C. S., … Sulas-Kern, D. B. (2020). The 2020 photovoltaic technologies roadmap. *Journal of Physics D: Applied Physics*, *53*(49). Scopus. https://doi.org/10.1088/1361-6463/ab9c6a

Yin, R. K. (2018). *Case study research and applications: Design and methods* (Sixth edition). SAGE.

ZonNext. (n.d.-a). *Tweedehands zonnepanelen*. Retrieved 29 July 2022, from https://zonnext.nl/producten

ZonNext. (n.d.-b). *ZonNext Projecten*. Retrieved 20 November 2022, from https://www.zonnext.nl/projecten

ZonNext. (n.d.-c). *ZonNext—Weeshuis voor Zonnepanelen*. Retrieved 12 July 2022, from https://zonnext.nl/

ZonNext. (2021). *Impact Rapport ZonNext* [Impact Report]. https://www.zonnext.nl/media/ZonNextImpactRapport.pdf

APPENDIX A – Selected Literature

Based on initial scanning of each literature result the following literature (Table 4) were selected for analysis during the literature review. Selection was based on the which life extension strategy was discussed as primary focus area. This includes research on the state-of-the-art of a given strategy, outcomes of tests for new approaches to, e.g., delamination, limitations to a particular strategy and the potential impact from a particular life extension strategy.

*Table 4: Identified literature per relevant life extension strategy, * indicated literature discussing multiple life extension strategies*

R-Ladder Strategy	Current Literature	Link between PV & R-Ladder Strategies / Notes	Keywords
R3 Reuse	(Walzberg et al., 2021)	Consideration of social factors in evaluating the impact of interventions to, e.g., change attitudes about used PV, boosting Reuse of modules	N/A
	(Franco & Groesser, 2021)	Identified CE challenges related to Reuse: lack of accurate data on PV failure, concerns regarding warranties, reliability and safety, and costs of second-life modules in relation to new ones	• Solar PV • EV batteries • Circular economy • Circular photovoltaic industry • PV Reuse • PV recycling
	(Murakami et al., 2021)	Describes a method for calculating amounts of potentially reusable PV modules and surveyed consumer decision making in disposal of functioning PV modules in Tokyo	• Waste PV panels • Generation forecast • Consumer's intention • Tokyo

R4 Repair	(Maceno et al., 2022) *	Circular Economy Toolkit results indicate great potential for Repair and remanufacturing	• Circular economy • Life cycle assessment (lca) • Photovoltaic solar panels
	(Tsanakas et al., 2020) *	Discusses the status and challenges regarding PV Repair/Refurbishment	• PV recycling • PV re-use • PV Refurbishment • Circular business model • Second-life PV modules
R5 Refurbishment	(Tsanakas et al., 2020) *	Discusses the status and challenges regarding PV Repair/Refurbishment	• PV recycling • PV re-use • PV Refurbishment • Circular business model • Second-life PV modules
	(Glatthaar et al., 2017)	Presents a c-Si PV recycling concept that evaluates options for Refurbishment before recycling the module	• PV modules • Silicon Solar Cells • Recycling • Encapsulation
	(Gautam et al., 2022) *	Describes feasibility for small and medium sized enterprises to apply CE based business models, applying Refurbishment and remanufacturing, for EoL PV waste in developing countries	• Solar PV • E-waste • Circular economy • Circular supply chain • Recycling
	(Charles et al., 2017)	Examines lifecycle optimisation for 3rd generation PV along with the potential for recycling and Refurbishment strategies	• N/A

	(Gautam et al., 2022) *	Describes feasibility for small and medium sized enterprises to apply CE based business models, applying Refurbishment and remanufacturing, for EoL PV waste in developing countries	• Solar PV • E-waste • Circular economy • Circular supply chain • Recycling
	(Schoden et al., 2022)	Investigates the potential to Remanufacture dye sensitised solar cells into new cells using Remanufactured components, showing similar or higher efficiencies and the ability to Remanufacture multiple times	• Circular economy • Dye-sensitized solar cell • Remanufacturing • Sustainability
R6 Remanufacturing	(Heath et al., 2020)	Mentions how reused cells may not provide as much value compared to recycling, given the lifespan and efficiency	• N/A
	(Deng et al., 2021)	Circular use of recovered intact silicon wafers from EoL PV can aid in reducing manufacturing cost of second-life PV modules	• Economic assessment • End-of-life • PV circular economy • PV recycling • PV remanufacturing • Second-life modules • Silicon wafer recovery
	(Park et al., 2016)	Describes a process for reclaiming wafers from c-Si PV modules showing properties similar to virgin silicon wafers and	• N/A

		Remanufactured modules with similar efficiencies to the initial cell	
	(Bombach et al., 2006)	Demonstration of intact silicon recovery from an early 23-year-old PV plant (constructed in 1983) and remanufacturing into new modules with increased efficiency	• Recycling • PV Module • Silicon
	(Lee et al., 2018)	Describes a pre-treatment to intact cell recovery by cracking the front glass and patterning the EVA encapsulant, with a reclaimed efficiency of 18,5% vs for 18,7% a new cell	• Efficiency • Reclaimed wafer • Recovery • Solar cell • Unbroken solar cell
	(Einhaus et al., 2018)	Demonstration of recovery and Reuse of glass from NICE PV modules and the potential for Reuse of other components in new products through remanufacturing	• N/A
	(Maceno et al., 2022) *	Circular Economy Toolkit results indicate great potential for Repair and remanufacturing	• Circular economy • Life cycle assessment (lca) • Photovoltaic solar panels

APPENDIX B – Rejected Literature

Irrelevant literature was rejected for further analysis in the literature review based on, among others, relevance, focus area and specificity. Reasons why a specific piece of literature was not included in the analysis is provided (Table 5).

Table 5: Literature rejected from final analysis; reasons provided per item

Literature	Reason for Exclusion	Keywords
(Obrecht et al., 2022)	Aims to forecast the availability of used, operational EV batteries	• Electricity storage • Scenario analysis • Battery electric vehicle • EV • EOL • Beyond end-of-life • Forecast • Photovoltaic • PV • Self-sufficiency
(Charles et al., 2019)	Discusses battery selection for small-scale domestic PV installations in Sub-Sharan Africa based on environmental impacts and availability of recycling infrastructure	• Solar energy • Batteries • Circular economy • Critical materials • Africa • End-of-life
(Kim & Park, 2018)	Discusses PV waste scenarios for South Korea & minimal waste stream requirements for local & international recycling infrastructure	• Circular economy • Solar PV deployment • PV waste • Recyclable materials

		• Weibull distribution function • South Korea
(Rahmani et al., 2022)	Defines and determines residual value of power electronics on a component basis towards Reuse, not related to PV	• Design for Reuse • Design for Modularity • Design to Environment • Ecodesign • Power electronics • Lifetime Monitoring • Extended Lifespan • WEEE
(Iturrondobeitia et al., 2022)	Study assesses environmental impacts of aqueous zinc ion batteries using cradle-to-gate LCA	• Aqueous zinc-ion batteries • Circular economy • Energy storage • Environmental impacts • Life cycle assessments
(Salim et al., 2021)	Describes the design of a serious game to improve understanding and stakeholders' ability for decision-making in enabling PV panel EoL management	• Solar panel • Photovoltaic • Product stewardship • Circular economy • Serious game • Stakeholder engagement
(Abokersh et al., 2021)	Sustainability analysis of a high temperature thermal energy storage system using molten salt as part of a concentrated solar power plant	• Circular economy • Concentrated solar power • Life cycle assessment (LCA) • Material circularity index • Sustainability

		• Thermal energy storage (TES)
(Ansanelli et al., 2021)	Gate to gate LCA on a new PV recycling technology, does not go into any product life extension strategies	• Crystalline silicon photovoltaic (c-Si PV) panels • End-of-Life PV panels • Life Cycle Assessment (LCA) • Recycling, recovery • Secondary materials
(Husgafvel et al., 2021)	The study addressed sustainable and CE oriented public procurement for a specific region in Finland	• Circular economy • Kymenlaakso • Public procurement • Sustainable
(Guerin, 2020b)	Demonstrates local circular use of EoL packaging materials to a utility-scale solar electricity construction site	• Circular economy • Construction waste • Cost-benefit analysis • End-of-life packaging materials • Solar PV plant
(Brenner & Adamovic, 2020)	Discusses aesthetic application of BIPV, PV recycling efforts and design to integrate flexible PV in various products and pieces of public infrastructure	• Building-integrated photovoltaics BIPV • Circular economy • Innovation; Photovoltaics PV; Standardization; Sustainability
(Chazarra-Zapata et al., 2020)	Discusses the benefits of using PV for irrigation in the South-East of Spain	• Circular economy • CO2 reduction

		• Irrigation modernization • Sustainable agriculture • Water Reuse
(Guerin, 2020a)	Enabling on-site Reuse of EoL packaging waste streams containing cardboard and wood at utility-scale solar energy site	• Circular economy • Cost-benefit analysis • Mulch • Packaging • Waste
(Hsu & Lin, 2019)	Production efficiency and waste treatment in husbandry industry in Taiwan	N/A
(Nakakura et al., 2019)	Describes conjugate analysis of radiation, convection and conduction of heat transfer in the volumetric receiver for concentrated solar and solar fuel production	• Circular economy • Design for disassembly and Reuse • Integrated collector-storage solar water heater • Life cycle assessment
(Cusenza et al., 2019)	Identify optimal battery energy storage system size for load match optimization and environmental impacts in a life cycle perspective, using retired electric vehicle batteries	• Battery storage system • Electric vehicle battery • Life cycle assessment • Load match • Second life application
(Bertino et al., 2019)	Circular interventions applied to a building in Vienna, focusing on the optimal management of resources throughout the life cycle of new or existing buildings	• Circular economy • Innovative use of secondary resources • Nature-based solutions • Resource and energy efficiency

		• Service-driven business models • Technological innovation
(Palitzsch et al., 2018)	Describes results from an optical recycling technology for c-Si PV modules to recover high purity glass and silicon	• CdTe • CIGS • Circular economy • EOL • Gallium • Glass • Indium • Laser • Photovoltaic scrap • Recycling • Silicon • Thin film photovoltaic • Waste
(Palitzsch, 2018)	Novel PV recycling process focussed on high-value glass recovery	• Circular economy • EOL • Glass • Indium • Photovoltaic scrap • Recycling • Silicon • Silver • Thin film photovoltaic • Waste
(Bobba et al., 2018)	LCA study assessing the benefits and drawbacks to using repurposed EV batteries in second-life applications	• Battery second-use • Electric Vehicles (EVs)

		• Environmental impact • Life Cycle Assessment (LCA) • Repurposing • Reuse
(Uggetti et al., 2018)	Description of an experimental microalgae-based waste water treatment system	• Bioplastics • Circular economy • Closed systems • Microalgal biomass • Wastewater
(Dominguez et al., 2018)	LCA of three greywater Reuse scenarios	• Life cycle assessment (LCA) • Light emitting diodes (LEDs) • Membrane biological reactor (MBR) • Photocatalysis • Photovoltaic solar energy
(van der Roest et al., 2017)	Study on converting waste toilet paper into electricity with a LCOE comparable with that of residential PV	• Cellulose • Circular economy • Energy conversion • Gasification • Sustainable chemistry • Waste Reuse
(*2nd International Conference on Green Building, Materials and Civil Engineering, GBMCE 2013*, 2013)	Conference review, some of the 401 papers mention PV or Reuse but never within the context needed for this research	N/A
(Mendoza et al., 2019)	Discusses the environmental impact of home-made solar cookers using household materials, compared to conventional microwaves	• Circular economy • Do-it-yourself (DIY)

		• Eco-design • Life cycle assessment (LCA) • Life cycle costs (LCC) • Social sustainability
(Lameh et al., 2021)	Investigates the use of concentrated solar energy for pyrolysis of high-density polyethylene, to evaluate the environmental performance	• Process modelling • Pyrolysis • Simulation • Solar energy • Solar thermochemical system
(*2016 Electronics Goes Green 2016+, EGG 2016*, 2017)	Conference review, some of the 73 papers mention PV or remanufacturing but never within the context needed for this research	N/A
(Erol et al., 2022)	Scored restraining and driving forces for CE implementation for solar and wind supply chains in Turkey	• Circular economy • Solar photovoltaic energy supply chains • Wind energy supply chains • Neutrosphopic-DELPHI-based Force Field Analysis • Neutrosphopic-DEMATEL
(Tan et al., 2022)	Discusses more accurate PV operating lifetime prediction by considering technical, economic and social reasons for decommissioning, specifically for Australia	• Solar photovoltaic module lifetime • End-of-life management • Circular economy
(Miettunen & Santasalo-Aarnio, 2021)	Primary focus is on recycling of dye-sensitised solar cells, they do discuss Reuse of individual components but describe it as unlikely or challenging	• Eco-design • Photovoltaics • Dye sensitized solar cells • Material development • Recycling

		• Circular economy
(Daljit Singh et al., 2021)	Study analyses three different PV EoL scenarios in Australia via LCA, no specific mention of PLE strategies besides mentioning that durable, long lasting PV modules are a more viable option for reducing environmental impact than recycling	• Circular economy • LCA • Photovoltaic panels • Recycling • Circular design • Carbon emissions
(Contreras-Lisperguer et al., 2021)	Discusses material separation for c-Si PV modules and evaluates the performance of a proposed model of a closed-loop material cycle to assess the flow of silicon, aiding future planning and logistics of circular PV	• Photovoltaic • Cradle-to-cradle • Closed-loop-cycle • Upcycling • Recycling • Circular economy
(Ovaitt et al., 2021)	Explores future trends to predict the percentage of installed capacity comprising of bifacial PV modules by 2050	• Circular economy • Photovoltaics • Energy return on investment (EROI) • Bifacial • Technology evolution • Reliability • Repair • Reuse • Recycle
(Mahmoudi et al., 2020)	The focus was on economic feasibility of recycling plants and optimising recycling processes from environmental and economic perspectives	• End-of-life photovoltaic • End-of-life PV module • LCA • Waste management • Cost-effective analysis

		• Techno-economic analysis
(Takada et al., 2020)	Describes a process for achieving multiple material life cycles by recycling organic solar cells	• Zinc oxide • Organic electronics • PBDB-T • Nonfullerene acceptors • Recycling
(Amato & Beolchini, 2019)	The focus was on Indium and Gallium recovery from EoL CIGS PV modules as a secondary materials source	• CIGS photovoltaic panel • Critical raw materials • Gallium • Indium • Metals extraction

APPENDIX C – Interview Protocol

As part of a multi-method research project into the theory and practical applications of product life extension strategies for photovoltaics in the Netherlands, a series of interviews will be held with those currently practising these strategies. Whereas prior theory has indicated both the relevance and feasibility of several R-Ladder strategies for product life extension, including Reuse, Repair, Refurbishment and Remanufacturing, these interviews are meant to deepen the understanding of the underlaying challenges and benefits to practising these strategies in a real-world setting.

Interview Structure

The interview will follow a semi-structured design to ensure answers to several baseline questions for later comparison between cases and to allow for sufficient opportunity for the interviewee to interdict and present additional insights that are deemed important. It further adds the benefit of allowing for follow-up questions to answers that would otherwise not fully answer the initial question or if further details could add valuable information.

Each interview will be held either face-to-face or via videocall, depending on availability of the interviewee, willingness to meet face-to-face, changing or unforeseen circumstances, and to allow for interviews to be scheduled on a relatively short time-frame. The goal is to interview at least 3 parties for the case study phase, covering at least 3 separate product life extension strategies.

With permission of the interviewee, the interviews will be recorded for later transcribing and analysis. In the case of a face-to-face interview recording will be done using a (lavalier) microphone and computer to ensure recording quality. The video-call interviews will be recorded using the recording functionality included in the software. The lack of control over the microphone used by the interviewee is seen as an acceptable risk that may increase the time needed to transcribe the interview manually.

Result analysis

Interviews will be transcribed using intelligent verbatim transcription to filter out filler words, repetition, ramblings, pauses and irrelevant noises. Transcribed text will be coded using, initially, open coding to extract the main themes from each text fragment. This will be followed by axial coding to categorise and organise similar and relevant codes into common themes. These themes are to be linked to each of the R-Ladder strategies to identify the challenges and benefits to each strategy.

Initial Interview Questions

The following questions were only used during the first interview. After which was decided to simplify the interview process and questions to brief interviews (30-45 minutes) on a few main discussion points. This allowed for more interviews and thus more diverse perspectives on the matter.

Background & Organisation

- Can you briefly introduce yourself and your organisation?
- What is your personal or prior connection to solar PV?
- What was the primary driver for the foundation of your organisation?
- What goals do you aim to achieve?
  - In day-to-day operations?
  - As an ultimate or long-term goal?
- What have you been able to achieve so far?
- Where would your organisation fit within the solar PV value chain?
- What makes your organisation unconventional?
  - Which of your activities would you view as conventional?

Opportunities & Barriers/Challenges

- Where there any specific conditions needed for your (PLE) strategy to succeed?
  - If so, which and why?
- What are the main benefits to your approach?
  - How did these offer advantages?
- What challenges have you experienced so far?
- How did you overcome these?

Circular Economy, CRM & PV Design

- Which (Circular) life extension strategies best describe your organisation? (Reuse, Repair, Refurbishment, Remanufacturing or otherwise?)
- How would you describe the role of your organisation within a Circular Economy for solar PV?
- What is your impact on the material demand for solar PV?
  - And specifically for Critical Raw Materials?
- How much extra life do you add to existing PV modules?
- How do you view the current design of PV modules in relation to the life-extension strategies your organisation performs?
- What about current solar PV could be improved going forward?

Discussion Points
PLE practitioners

General

- Introduction
- The ‘why’ behind the story / organisation?

PLE strategy & circular PV

- Conditions needed for this PLE strategy / circular PV?
- Benefits to this approach?
- Challenges to this approach?
    - Economic
    - Environmental
    - Technology
    - (Critical)raw material use & selection
- View on PLE strategies?
- How much extra life given to the modules?
- View on PV design trade-offs?
    - Economic
    - Environmental
    - Technology
    - (Critical) raw material use

Flowchart

- Discuss R-Ladder Flowchart

Discussion Points
PV Experts

General

- View on premature replacement?
- View on using PV for as long as possible?
- Dealing with EoL PV?

PLE strategy & circular PV

- Challenges for PV?
    - Economic
    - Environmental
    - Technology
    - (Critical)raw material use & selection
- View on PLE strategies?
    - Reuse
    - Repair
    - Refurbishment
    - Remanufacturing
    - Repurpose
- View on multiple life cycles?

Flowchart

- Discuss R-Ladder Flowchart

APPENDIX D – Members of Holland Solar

Organisation	PLE Strategy
123 Zon & Energie	N/A
365 Zon	N/A
4 Solar	N/A
ABO Wind	N/A
Activum Groen Lease	N/A
Agrisun	N/A
Alius	N/A
Almelektro	N/A
Ariens Solar BV	N/A
Atama Solar Energy BV	N/A
Atlas Power	N/A
Awizon BV	N/A
Axiturn	N/A
BayWa r.e. Solar Systems	N/A
BeSolar Store	N/A
Bespaarpartner	N/A
Bezonnen Energie	N/A
BHM Solar	N/A
Blue Bear Energy	N/A
Bongo Solar	N/A
Bosch & van Rijn	N/A
BT Duurzame Installatietechniek	N/A
Canadian Solar NL	N/A
Chint Solar Nederland	N/A
Climate for Life Group	N/A
CMS Energiesystemen BV	N/A
Covolt	N/A
De Beijer RTB bv	N/A
De Centrale BTW Teruggave	N/A
De Laat Solar Systems	N/A
Delta Electronics	N/A
Dijkman Zonne-energie	N/A
Draaistroom Nederland	N/A
Duramotion BV	N/A
Dutch New Energy Research	N/A
Dutch Solar Energy	**Repair**
Dutch Solar Parks	N/A
Duurzaam Besparen	N/A
Duurzaamheidsteam	N/A
Duurzame Ontwikkelingsmaatschappij Holland	N/A
Easydura B.V.	N/A
Ecodome BV	N/A
Econic	N/A
Ecorus BV	**Repair / Replace**
EigenEnergie.net	N/A
eL-Tec Elektrotechnologie BV	N/A
Elsun	N/A
Eneco Solar & Wind	N/A
Energie Unie	N/A
Enie.nl	N/A
Enovos Green Power	N/A
Escom B.V.	N/A
ESDEC	N/A
Essent	N/A
European Solar B.V.	N/A
Eversheds Sutherland	N/A
Expert Solar Systems	N/A
Fronius	N/A
G2 Energy	N/A
Good!	N/A
Green IPP	N/A
Green4Energy	N/A
Greenfocus	N/A
GreenPowerSystems	N/A
Greeny Bros	N/A
Groendus	N/A
GroenLeven	N/A
Groenpand BV	N/A
Growatt New Energy B.V.	N/A
GSE Intégration	N/A
Hesi installatie techniek bv	N/A
Heylen Warehouses	N/A
HRsolar groep	N/A
Huawei Digital Power Technologies	N/A

HVC	N/A
IBC Solar	N/A
ICE Energy	N/A
IDenergie BV	N/A
IJsselEnergie B.V.	N/A
Ik ben Ra	N/A
In2Solar	N/A
Infinity Solar Nederland B.V.	N/A
Intellisol	N/A
IX Zon	N/A
IZEN	N/A
Jacobs Energy Care B.V.	N/A
JansZon B.V.	N/A
KiesZon	N/A
Kiwa BDA	N/A
Klimaatfonds Nederland	N/A
Koolen Industries Solar BV	N/A
Koolen Solar Projects	N/A
Krannich Solar B.V.	N/A
LC Energy	N/A
Lens	N/A
Libra Energy	N/A
LightsourceBP	N/A
MB Zonnepanelen	N/A
Mijn Energie Brabant	N/A
Mijn Zonneveld	N/A
MobiSolar B.V.	N/A
NaGa Solar Holding B.V.	N/A
Nara Solar	N/A
Natec	N/A
Navetto	N/A
Nefit Bosch	N/A
New Energy Systems	N/A
Next Kraftwerke	N/A
Nixwell B.V.	N/A
NovaVolt	N/A
NRG2all BV	N/A
NuytGroep B.V.	N/A
Oceans of Energy	N/A
Odura	N/A
Oranjedak Energy	N/A
Over Morgen	N/A

Patina Energy BV	N/A
Peeters Duurzaam B.V.	N/A
Ploum	N/A
Pondera Consult BV	N/A
Powerfield Realisatie & Exploitatie BV	N/A
Profinergy B.V.	N/A
Pure Energie	N/A
PVO International	N/A
Raysol	N/A
RE-Source Duurzame Installaties BV	N/A
Remeha BV	N/A
RenCom	N/A
RenewabLAW	N/A
Resolar B.V.	N/A
Rexel Nederland B.V.	N/A
RWE	N/A
Scholt Energy	N/A
Schooldakrevolutie	N/A
Segno Energy	N/A
SGZE	N/A
ShareNRG B.V.	N/A
Shell	N/A
SinneTechniek	N/A
SMA Benelux	N/A
So Sustainable	N/A
Solar Art BV	N/A
Solar Cleaners	N/A
Solar Concept	N/A
Solar Construct Nederland	N/A
Solar Crew	N/A
Solar Edge Technologies	N/A
Solar Electricity Development	N/A
Solar Energy Booster	N/A
Solar King	N/A
Solar Magazine	N/A
Solar Noord	N/A
Solar Noord-Holland	N/A
Solar Solutions Int.	N/A
Solar Tester	N/A
Solar Totaal Advies	N/A
Solarclarity	N/A

SolarComfort B.V.	N/A
SolarEnergyWorks	N/A
SolarDistri B.V.	N/A
Solarfields	N/A
Solarge BV	N/A
Solarif Insurance	N/A
Solarpartners	N/A
Solarplaza International BV	N/A
SolarProf b.v.	N/A
SolarSense	N/A
SolarSteijns	N/A
Solarstell	N/A
SolarToday BV	N/A
Solarus Smart Energy Solutions BV	N/A
Solarwatt BV	N/A
Solcol	N/A
Soleila	N/A
Solinso	N/A
Solisplan	N/A
Solora B.V.	**Repair / Replace**
Soltec Services	N/A
Soltronergy	N/A
Stafier Solar Systems	N/A
Statkraft Markets B.V.	N/A
Straightforward	N/A
Sunbeam BV	N/A
Sunforce Duurzame Energietechniek	N/A
Sungrow	N/A
SunNed BV	N/A
Sunprojects B.V.	N/A
SunRidge BV	N/A
Sunrock	N/A
Svea Solar Nederland B.V.	N/A
Switch Energy	N/A
Switch2Solar	N/A
Techniq Energy	N/A
Technique Solaire	N/A
TKI Urban Energy	N/A
TNO	N/A
Tomorrow Energy B.V.	N/A
TPSolar Nederland B.V.	N/A
Trio Investment	N/A
Triple Solar BV	N/A
Tummers Solar Installations	N/A
TW!ST	N/A
VaConsult	N/A
Van Bijsterveld BV	N/A
Van den Pol Elektrotechniek	N/A
Van der Valk Solar Systems	N/A
Van Herp Solar Solutions B.V.	N/A
VanderLinden	N/A
Vattenfall	N/A
VDS Solar Systems	N/A
Ventolines	N/A
Viridian Solar	N/A
Volta Solar BV	N/A
Wasco	N/A
Weidmüller	N/A
Youen Installatie BV	N/A
Ysubsidie	N/A
Zeeuwind	N/A
Zelfstroom	N/A
Zoekomst	N/A
Zon&Co	N/A
ZON7	N/A
Zonatlas NL B.V.	N/A
Zondermeer	N/A
Zonel Energy Systems / Joulz Zonne-energie	N/A
Zonne Energie Oost	N/A
Zonnefabriek	N/A
Zonnegilde B.V.	N/A
Zonnemarkt BV	N/A
Zonnepanelen Parkstad BV	N/A
Zonnepanelen Xtra	N/A
Zonnepanelendelen.nl	N/A
ZonnepanelenSuper.nl	N/A
Zonnepark Services Nederland	N/A
ZonneStroom Amsterdam-Solar	N/A
ZonPiek zonnepanelen	N/A
Zonzo B.V.	N/A

APPENDIX E – Marktplaats Analysis Data

To gain a better understanding of the consumer-to-consumer or informal second-hand PV module market, advertised PV modules on de Dutch second-hand sales platform ‘Marktplaats’ were gathered and analysed (Table 6). Primary focus was on the number of modules on sale, their performance, age and the primary motivation for sale.

Table 6: Results from the advertisements analysis on Marktplaats for used PV modules

Number of panels	Performance (Wp)	Age (years)	Reason for sale
2	50	N/A	N/A
19	50	N/A	N/A
55	50	N/A	N/A
300	50	N/A	Degradation
24	65	N/A	Surplus
20	75	N/A	N/A
27	75	N/A	N/A
50	75	N/A	N/A
4	85	N/A	N/A
24	85	N/A	Unnecessary
54	85	N/A	Upgrade
4	86	N/A	N/A
2	110	N/A	N/A
6	110	N/A	Upgrade
20	110	N/A	Upgrade
39	110	N/A	N/A
70	150	5	N/A
27	155	N/A	N/A
19	165	6	Upgrade
21	165	21	N/A
14	170	5	N/A
120	175	20	Upgrade
21	165	N/A	N/A
9	180	12	Upgrade
80	180	12	Upgrade
16	185	11	Renovation
N/A	175	20	Renovation
6	190	10	Upgrade
6	190	10	N/A
12	200	10	Upgrade
25	230	8	N/A
18	235	10	Upgrade
3	190	N/A	N/A
12	240	10	Upgrade
56	240	10	N/A
18	245	10	N/A

	18	245	9	N/A
	2	221 N/A		N/A
N/A		225	10	N/A
	3	250	8	N/A
	3	250	8	N/A
	20	250	8	Renovation
	1	240 N/A		N/A
	8	240 N/A		N/A
	10	240 N/A		N/A
	20	250	8	Renovation
	12	240 N/A		N/A
	15	240 N/A		N/A
	15	240 N/A		Damaged
	8	255	9	Upgrade
	100	240 N/A		Weight
	10	245 N/A		Upgrade
	8	255	9	N/A
	23	255	6	N/A
	40	255	7	Renovation
N/A		245	5	Repower
	1	250 N/A		Surplus
	1	250 N/A		Surplus
	2	250 N/A		N/A
	2	260	2	N/A
	6	260	5	N/A
	8	250 N/A		Upgrade
	10	250 N/A		Renovation
	12	250 N/A		Upgrade
	12	260	8	N/A
	20	250 N/A		N/A
	30	260	7	N/A
	1	265	7	Surplus
	6	265	5	Upgrade
	27	250 N/A		N/A
	1	255 N/A		N/A
	5	255 N/A		N/A
	49	265	6	N/A
	6	270	5	N/A
	13	255 N/A		N/A
	22	255 N/A		N/A
	10	270	5	N/A
	28	270	5	N/A
	200	270	5	N/A
	5	275	5	N/A
	8	260 N/A		N/A
	7	275	3	N/A
	20	280	4	Upgrade

9	290	6	N/A
12	290	6	Upgrade
5	295	3	Upgrade
2	265	N/A	N/A
10	300	6	Unnecessary
10	300	3	Upgrade
2	325	1	Upgrade
2	365	1	N/A
1	395	1	Renovation
1	395	1	Surplus
1	410	2	Surplus
N/A	270	N/A	N/A
N/A	270	2	N/A
1	275	N/A	Surplus
1	275	N/A	N/A
3	280	N/A	N/A
9	285	N/A	N/A
1	315	N/A	N/A
12	315	N/A	N/A
2	320	N/A	N/A
16	320	N/A	N/A
1	325	N/A	Surplus
1	325	N/A	N/A
1	330	N/A	N/A
3	380	N/A	N/A
3	380	N/A	N/A
1	400	N/A	N/A
N/A	460	N/A	N/A
1	N/A	N/A	Surplus
4	N/A	N/A	N/A
8	N/A	N/A	Surplus
8	N/A	N/A	N/A
18	N/A	N/A	N/A
20	N/A	N/A	N/A

APPENDIX F – Interview Notes & Coding Boldz

The following shows a summary of the transcribed interview with Boldz, initial coding round and the final categorisation and selection of relevant codes.

Interview Summary

The volume of modules taken from roofs was significant enough to be noticed, some with damaged others fully intact, and most still functional. Some only ±5 years old and discarded for various reasons. There was no clear pathway for these modules, repurposing them was one options, Repair another. This led to the founding of this company. An early realisation was the challenge of creating an economically/commercially viable business.

One aim was to make the concept of circularity more tangible by showcasing it in the form of a product that people can use. While acknowledging that this will not solve the pending waste challenge for future PV modules, it does show that these older modules are still useful and can be utilised in other ways than originally intended. PV has already developed to a point where it provides an affordable alternative to fossil fuels, the challenge to the EoL aspects remains. This ties in with the business' core values of energy, sustainability and circularity. An advantage to the approach is that it makes second-life PV visible for a wider audience.

Their specific application uses modules, typically around 6 years old, with an original performance of around 250 Wp of which over 90% still remains. In horizontal orientation and covered with a foil to make the surface more comfortable for use as a picnic table, that leaves around 100 Wp. Sufficient for charging mobile devices.

Another part of the business is in PV Repair, specifically towards developing a Repair technique for glass-glass modules that are expected to gain popularity. This may eventually offer an opportunity to Repair thousands of broken panels in the future. For current glass-foil modules the issues they experience include 'soiling', frame damage, bypass-diodes entire junction-boxes or issue with cables and connectors. Some of these are easy to fix, but bypass diodes require specific replacements parts. For other Repairs, such as the junction-box, it is simply not feasible due to the low volumes.

There is currently a gap for establishing the value of (prematurely) discarded PV modules, it seems not always clear whether there is any value left in used PV. On the other side, the costs for labour, testing, certification, transport and preparation for installation remain significant. In the Netherlands, labour is expensive and space is scarce, meaning that second-life PV has to compete with newer technologies in performance per square meter and on cost. It also lacks the assurances that new modules enjoy, such as a factory warranty and generation guarantee.

Second-life modules do have a place in the Netherlands, but one should look for creative applications and in places where spatial constraints are less of a factor. This may include integration in infrastructure and other surfaces. In those cases, it becomes a trade-off between upfront cost and eventual return on investment. With increasing virgin material prices Reuse becomes more interesting.

Recycling does not offer the end-all solution to EoL PV, technological development for recycling needs to develop further. It further depends largely on the volume of discarded modules. EoL processing now is largely downcycling.

Ideally PV modules would be manufactured without the use of PFAS, in countries with a high-renewables energy-mix, better labour conditions and with an encapsulant that can be more easily separated from the rest of the materials. It remains a trade-off between very long-life and harder to disassemble or a more modular approach that may introduce a higher risk of failures. Current business models account for the upfront costs to be relatively high and the operational cost to be very low, as is the case now. Introducing a variable such as a 'revive' or module 'repowering' every 10 years would make the business case more complex for investors, perhaps too much of a risk. Economics remain important to the success.

From an environmental point of view, a modular approach would be preferable. Under the assumption that labour and time are non-scarce resources, it would be possible to open up a module and swap out several cells. It depends on which resource is deemed scarce/limited, it's a trade-off.

Initial Coding Results

Abstract concept
Assurance/certainty
Availability of used products
Background
Background
Background
Background
Background
Background
Business opportunity
Changing contextual factors
Circular Economy
Circularity
Circularity
Commercial solution
Component replacement
Context
Contextual factors
Contextual factors
Contributing factors
Conversation starter
Costs
Costs
Credibility
Degradation
Degree of damage
Degree of damage
Degree of damage
Degree of damage
Degree of damage
Degree of damage
Design for disassembly
Design for EoL trade-offs
Design for Long-Life
Design for Long-Life
Design trade-off
Disassembly
Downcycling
Economic challenges
Economic challenges
Economic challenges
Economic conditions
Economic conditions
Economic constraints
Economic opportunities
Economic opportunities
Economic opportunities
Economic opportunity
Economic priorities
Economic return on investment
Economic trade-off
Economic trade-off
Economic uncertainties
Economic uncertainties
Ecotoxicity
Efficiency
Efficiency
Efficiency
End-of-Life
Energy
Energy
Energy-mix
Exchange of expertise
Expected lifespan
Experiences from companies
Experimenting
Failure ratio
Focus
Function
Functional used modules
Goals
Goals
High-value recycling
Idea to concept
Impact limitations
Impact quantification
Importance for energy transition
Indirect impact
Inspector for Reuse
Installed capacity
Integration
Investment decisions
Labour costs
Labour scarcity
Lacking destination
Lacking technological developments
Life extension
Lifespan
Lifespan
Market expectations

Market gap
Market trends
Material costs
Material opportunities
Material use
Materials
Modular design
Module cleanliness
Not a definitive solution
Opportunities
Opportunity
Performance
Premature discarding
Premature discarding
Problem recognition
Product requirements
Proof-of-Concept
PV module design
Refurbishment
Refurbishment
Remanufacturing
Repair
Repair
Repair
Repair
Repair conditions
Repair limitations
Repair technique
Repair technique
Repair technique
Repair technique
Repair technique
Repairability
Repurpose
Repurpose
Reuse
Reuse
Reuse context
Reuse in a different context
Reuse in new context
Reuse opportunities
Risk management
Risk management
Risk management
Risks
Scale limitations
Scale limitations
Scope
Separation
Spare part availability
Spatial constraints
Spatial constraints
Subsidies
Subsidies
Sustainability
Sustainability
Talking point
Tangible product
Tangible product
Tangible product
Tangible product
Tangible solution
Technical limitation
Technical limitation
Technical limitations
Technological challenges
Technological challenge
Technological challenges
Technological development
Technological development of PV
Technological differentiation
Testing & Certification
Time constraints
Time constraints
Trade-offs
Twofold approach
Twofold approach
Uncertain application
Value creation
Value creation
Value proposition
Value proposition
Values
Values
Visibility
Volume constraints
Volumes
Warranty
Working conditions

Categorised & Reduced Codes

Abstract to Concrete
Abstract concept
Conversation starter
Indirect impact
Not a definitive solution
Problem recognition
Proof-of-Concept
Tangible product
Visibility

Economics & Investment Factors
Business opportunity
Commercial solution
Costs
Credibility
Economic conditions
Economic trade-off
Investment decisions
Labour costs
Market gap
Market trends
Material costs
Opportunities
Risk management
Subsidies
Twofold approach
Value proposition
Warranty

Practical Challenges
Availability of used products
Component replacement
Lacking destination
Repair conditions
Reuse context
Scale limitations
Spare part availability
Technical limitation
Testing & Certification
Time constraints

Product Conditions
Degree of damage
Efficiency
Failure ratio
Lifespan
Module cleanliness
Repairability

Design Trade-Offs
Design for disassembly
Design for Long-Life
Integration
Materials
Modular design
Product requirements
Technological differentiation

Circularity
Circular Economy
Disassembly
Downcycling
High-value recycling
Impact limitations
Life extension
Refurbishment
Remanufacturing
Repair
Repurpose
Reuse
Separation

Societal Factors
Ecotoxicity
Energy-mix
Importance for energy transition
Labour scarcity
Spatial constraints
Sustainability
Working conditions

Knowledge & Experience
Exchange of expertise
Experiences from companies
Technological development of PV

APPENDIX G – Interview Notes ZonNext

ZonNext realised there was high interest in PV Reuse, from both the supply and demand side. But testing and recertification/re-approval, to assure functionality, is not being done by anyone. There is a willingness to give away used modules, as long as they find a useful purpose. With assurance that everything still works.

ZN is a foundation, based on the ideas of circularity and Reuse, with respect for materials. The motivation originated in the knowledge of how EoL PV is currently processed; transported to another country and shredded (low-grade recycling/downcycling). Need to address this wrongdoing, this became a news item after which questions were asked in the Dutch House of Representatives; topic gained attention.

No lack of supply from parties that wanted a suitable new use case for their modules. Some sent to Ukraine, Africa and to schools.

Business case for second-life modules is not great, panels only make up around 1/3 of the total costs for a system + installation. Besides, the output of these panels is lower than new. Business is now paid through subsidies, unsure how it will be financed in the future.

Founder ZonNext, also founder at another social enterprise; Sungevity. They wrote an impact report (whitepaper) on the PV supply chain, upstream and downstream. Origin of panels, no always good. At EoL, unsure what happened with the modules. Not only wanting to gain attention for the wrongdoings, but also to provide a practical solution.

Ideally, you'd want to recycle and even upcycle existing modules, but that is not yet possible. As an in-between solution, you want to extend the lifespan for as long as possible. If and when it's possible to upcycle panels, there is no longer a need for ZonNext to exist, which is the ultimate goal of the organisation.

ZonNext collaborates with WEEE NL and Refurn (part of WEEE NL) for the collection and testing of used modules respectively. Goal is to work with 'Stichting OPEN' as well, since they are responsible for the collection and processing of PV modules as e-waste.

WEEE NL deals with ±1/3 of all PV collected and is the only party that checks the modules on functionality. After an optical inspection these modules are sent to ZonNext, where Refurn uses a flash-test to determine the performance of each individual module, which is more extensive than the testing in factories where they only test some of the modules they make. ZonNext's approach also means there is no transport to another country and no processing costs.

Second-life modules end up at larger projects with a few dozen households, delivering emergency power in Ukraine, on schools combined with an educational element on circularity and renewable energy, at the Ceuvel or at housing corporations for people in energy-poverty. The goal was to gain media attention for these issues, and to give the modules a social purpose/for the greater good. Examples of demonstrations, such as temporary floating solar setups, those modules will return to ZonNext.

Some parties have already promised ZonNext that they will get the used modules at end of use. Uncertain whether ZonNext will still be around by then.

No 3rd use-phase, panels are too old by then. For 2nd use only, ideally, panels of up to 15 years or from around 220-250 Wp.

APPENDIX H: Interview Notes PV Expert 1

TNO Expert on c-Si PV Technologies

Premature replacement/discarding?

Primarily economic reasons for replacement, systems are usually 10 years old when removed from a rooftop or elsewhere. Efficiencies have increased a lot, more energy per square meter, so has the desire to maximise yield per surface area.

Current installed capacity is not that high, but expectations for the future from today's installation and future installations may pose serious challenges. Question becomes; what is the total impact of replacement, and what to do with 'discarded' modules? Several options available; recycling, Reuse on buildings that are scheduled for renovation (temporary sites, where you don't need the full lifespan). Opposed to Reuse in, e.g., African countries with high irradiance due to transport and losing overview and control over these modules. Keep it local.

Repair, e.g., open up the back of a module to redirect a broken cell and use in context where energy density is less of a concern. Now ±10% of electricity from PV, but electricity is only 20-25% of total energy use. Now ±15 GW, plan to hit 200 GW in 2050.

Long lifespan?

In favour of long use, but there is a need for smart application, especially in the future with higher volumes.

EoL pathways?

Recycling and high-quality Reuse (of materials), e.g., for use in new PV or in battery technologies. Preferably in closed cycles.
In the early 90's cell thickness was about double that of today's cells, expected to reduce further, but quality of silicon metal from old cells is not as high as nowadays. Can remelt, to purify further. Processing can improve cell quality, but questionable whether we can achieve similar quality as new now. 3 energy intensive steps in silicon wafer manufacturing:

- *Creating metallurgical grade silicon from silicon-oxide*
- *Purification to solar-grade silicon*
- *Wafering*

Cell is around half of energy use in manufacturing, recovering the cell therefore has a large impact. As does recovery of silver.

Best PV technology from an LCA & energy payback time perspective is CdTe. But from a materials perspective those are not ideal. FirstSolar makes these, and reclaims and Reuses materials from recovered modules.
In NL, under WEEE legislation, only 80% recovery of total mass; glass + frame is already >80%

PV challenges?

3 important factors for PV:

- *High efficiency; helps reduce cost (40% of system is module, required surface area, cost and impacts are correlated),*
- *Integration; make invisible (NIMBY), integrate in mobility, infrastructure, etc.*
- *From renewable to sustainable, thus; circularity, reliability, etc.*

Economics: look at the value of PV, not at the price of PV. Integration increases value. We should not aim to achieve lowest possible cost anymore, especially since PV is already as cheap/affordable as it is. That means including public support and ecology in the value proposition.

CIGS technology is nearly dead, not enough resources to make sufficient CIGS for the energy transition (1TW capacity would exhaust global indium resources). CdTe has the largest share in thin-film, but is a very small player in Europe. Upcoming technologies; Perovskite, very few critical materials, but contains lead in small amounts (expected to find replacements). They do have an ITO-layer (Indium tin-oxide) which could become a bottleneck. Tin is a strategic concern (on the 3TG-list of conflict metals).

Goal now is to increase efficiency with the aim of reducing costs. Efficiencies can still double, halving the costs. Does require tandem/multi-junction. Changing composition changes band-gap.

PLE options?

No sufficient recycling methods available; downcycling. All focus was on packaging PV to last. Not made to take apart, making Repair, refurb, etc. difficult. In attempting to fix delamination issues with refurb, little chance as it would involve destructive disassembly (breaking cells, cracks), which is challenging to do economically.

Processing of older cells, given the improvements in processing tech, can gain efficiency provided that the cells can be recovered intact. Deutsche Solar, remanufacturing, achieving same performance (being the same materials and processes as the original by same company, does not apply to 3rd party and mixed tech). Doable on lab-scale, but questionable whether it is doable at large scale; expecting not to recover the cells intact.

Expert expectation; recover and reclaim silicon wafers in reasonable condition for remelting to grow a new ingot. Deems this processing step (one of the 3 most energy intensive for silicon wafer manufacturing) unavoidable. Unless different process used, apply design for recycling; for easier disassembly while preserving the long lifespan. Requires new materials, new encapsulants that can be released. Development of NICE-modules, only edge-sealed, negative pressure. Glass-glass, comparable to double-pane windows. Large potential for increasing sustainability through design (for recycling).

APPENDIX I: Interview Notes PV Expert 2

TU Delft Expert on PV Technologies

Premature replacement

Here (NL/EU), we have wealthy lifestyles and a consumeristic approach to PV; wanting the latest and greatest. As with cars, although it is a more involved purchasing process, as it takes more time and effort to design a system, install, etc.

Failure in PV occurs not very often. Most technologies have passed accelerated lifetime tests. Some can still fail in harsh environments, including urban environment with (partial) shading & thermal changes. This differs from PV in fields/plants where shade-mitigation is more common by using half-cut cells and split modules.

PV is designed for long life. Premature repowering depends on geographic location and grid capacity. Usually, owners want a uniform appearance on their roof, not replacing part of a system.

Integrated PV, requires good definition of integration; is it a building element; part of the roof structure that keeps out rain? May be more subjective in other use-cases, as norms and definitions get blurrier for other infrastructure. Aesthetics are also subjective, some like the blue cells and white backsheet. BIPV & custom PV = more expensive, but more options/solutions becoming available, it is gaining traction. Example of integrating in cars, where shapes differ a lot; challenge. For floating PV, the structures differ in their need to deal with specific conditions (waves, etc.)

Challenges

c-Si is the workhorse of the PV market. CRM acquisition is a main challenge, in both current and accelerated scenarios. Hetro-junction setups require transparent-conductive-oxides, contains indium. Research focussed on making this indium-free. And silver forms a challenge; the contacts contain silver. Although only ±10 mg per cell, each cell producing 5-5,5 W, scaling up to GWs in EU it adds up. Question whether we can keep up with production, would eventually need half of the global silver market for PV. Looking at copper as part of the solution, which has its own issues. Is applied differently in manufacturing, using electroplating, requiring chemicals. Dirty water that needs collecting and cleaning; wet chemical issues. Solution could be to print copper as is done with silver.

PLE as part of the solution?

Hetro-junction is not going too deep into the wafer, so if the wafer can be retrieved and the other materials removed, that could be impactful. The wafer is the major culprit for a PV module's carbon footprint; 50-60% of the total impact.

Question becomes, how do we recover the wafer in a gentle way? Since the surface cell & interface is hard to detach. What we do now is smashing and burning modules, burn off the polymers to detach the glass and wafer from the rest of the materials.

New module design without the molten polymer encapsulant aids direct recovery of cell and wet chemical processes can clean up the cell for Reuse. But that's not easy. The real breakthrough, for new encapsulants, expected form the chemistry sector. Two pathways:

- *Mechanical route; redesign PV modules with other encapsulants*
- *Chemical route; "activated" materials, acts as glue under normal use cases, but can be detached with a heat-trigger.*

APPENDIX J: Interview Notes PV Expert 3

PV Module Manufacturer

Premature Replacement

Premature discarding or replacement and not recycling PV causes environmental damage. Resource exhaustion is not addressed sufficiently.
Global installed capacity now is ± 1 TW, to achieve future goals we need 1 TW in additional capacity annually.

Currently, there is an economic case for replacement. Perhaps legal requirements are needed for minimal lifespan. Human behaviour plays an important role.

[Organisation] aims to be sustainable, starting with a minimal lifespan of 30 years, material choices (no lead-solder and PFAS-free). Currently there is antimony in the glass, to make it more transparent, but that makes it unusable in other sectors due to its toxicity. The glass is now "recycled" into, among others, glass wool insulation, which may get recycled into other products in a later life, including bottles. PFAS, another problem for the future.

Currently doing research with TNO to analyse options for reusing glass from used PV in new PV (TNO HERO), to keep antimony in a closed PV system.

With several issues the question of 'how' is not asked/answered; manufacturing and installation at the required scale. Are there even enough people to install all the PV we need? Is there enough material? Silver is scarce.

The energy demand for silicon wafer manufacturing is very high, increasing the energy demand further. Considerations exist for building nuclear power plants to provide energy for PV manufacturing.

PV PLE

Reuse, nice initiatives, also to gain further attention for the issue.
But for Repair, question of legal responsibility, who is responsible when a third party Repairs a known-brand PV module and sells it? And how are they being kept responsible for the costs that manufacturers pay in certification, which the Repairer does not have to pay for. Need for legal framework and CE-certification for Repaired PV.
Question is whether Reuse is economically viable, the labour needed to disassemble a system, or should we rather use it for as long as possible to postpone the waste challenge. Stichting OPEN, now collecting removal fees, but to what extent are they preparing for removal and EoL processing?
Eventually, a stream of panels will come, for which two pathways could be:

- *Recycling, high-grade*
- *To extract the last remaining energy from these modules*

Example of cases where on a residential rooftop where modules would be prematurely replaced, the "old" modules were moved to a north-facing rooftop rather than taken away and sent off for recycling. Even under non-ideal circumstances and indirect light, these modules still produce electricity and did not require transportation.

PV EoL

Development of a circular PV modules, which they want returned after use. Aim to reclaim the glass without contaminants for Reuse or to remelt in an oven. The encapsulant should act more like candlewax, with the ability to glue multiple times. Chemical composition of a new encapsulant is now in development. The encapsulant itself will not cause a massive waste issue, due to its volume.

If the glass can be removed cleanly, the Si, Cu and Ag can be recovered, which currently cannot be reused due to contamination from the thermoset encapsulant. Recovering the cells and reclaiming the silver would lead to the highest energy recovery/conservation, takes only a few steps to get it back to polysilicon.

To achieve current renewable energy generation targets, there isn't enough energy and aren't enough resources.

Currently, ingots produced in Norway are sent to China for wafer production.

Circular PV design?

- *Should be able to disassemble the module.*
- *Increase the number of recycled materials going into PV modules, provided that it does not negatively affect R-Ladder position at EoL*
- *Combine functionalities; PV rooftiles (no need for two separate functionalities, less labour needed to install two functions separately, aesthetics increases acceptance)*

Infrastructure; example of noise barrier, often considered too cumbersome or expensive by the organisations responsible for these barriers, wasted opportunity.

APPENDIX K: Interview Notes PV Expert 4

RIVM Expert on Safe & Sustainable PV

Premature replacement

Early replacement of PV; limited data available and limited attention on the topic.
Mostly based on people's experiences rather than quantities of data.

Potential environmental benefits are lost by early retirement of PV. Project developers, large scale installations, told that at inverter EoL they often replace the entire system (including PV modules), which is after 10-15 years.

For large scale installations they require permits for the land-use application, which are only given for a limited amount of time; ± 10-15 years. PV farms are likely built with that in mind. Difference between 15 and 30 years for the environmental impact is big. Premature replacement/discarding not yet viewed as a major issue.

PV Design

Modular PV would be a good next step, life extension would still be positioned above that. For used panels:

- *Export to a country with higher irradiance, within the EU*
- *Export to countries with even higher irradiance, e.g., Egypt or Morocco, with the added risks of losing control over the EoL processing*
- *Eventually, high-grade/purity recycling*

Inverters are not getting the same amount of attention, even though they are part of the reason why PV modules are replaced prematurely. Someone should research the impact of those.

In RIVM study the recycling scenarios do not take the recovery of CRMs into consideration, working under the assumption that those are not recovered. If recovered, that could lower the impact per kWh. PV cells seem like low hanging fruit for recovery, and Reuse for immediate benefit to environmental impact.

APPENDIX L: Interview Notes PV Expert 5

RVO Expert on Public Procurement

Circularity and sustainability are important factors, also in the PV sector. This led to the founding of the Fair Solar Network. There was also the question of impact from procurement: which critical factors to consider when buying PV? Be it on the level of a local government, organisation, et). Includes, among others, lifespan, Repairability, sustainability, inverter, etc. Procurement expertise centrum PIANOo; created a buyer group. Their role includes writing procurement texts, that can then be used by local governments, municipalities or other organisations.

Looking at the best options in the currently available offering. Used a request for information on lifespan and carbon footprint, which yielded good results. Requirements for procurement: trade-off between costs, environment, efficiency, lifespan, etc.

Another question is: do project developers even want this long lifespan?

- *Technology develops fast: more efficiency from new modules*
- *SDE subsidies, often for 15 years, that is what they base their business case on*
    - *Afterwards, panels shredded outside the NL or perhaps purchased*
- *Lot, land use rights, are only for a limited time*

Lifespan in many cases determined by external factors, not the technical lifespan. Difficult to plan for 25 years.

Opposing interests from importers, installer and retailers: want to sell as many as possible. Not interested in longer lifespan or long use. For second life modules, difficult to develop a business case. All costs at lower efficiencies are, relatively speaking, higher; labour, balance of system, etc.
One company in Germany warehousing old modules and offers them as replacement units for existing plants, at very high prices.
Choice is often up to the party purchasing the modules. Also at government, with SDE subsidies, 'Groenregeling', cheaper loans at a bank, etc. Should, for example, get better financing at lower footprint and without toxic materials.

CRM often not viewed as an issue, only used in low amounts and are deemed replaceable.

Energy needed to make PV in China is very cheap, they use a lot of coal power, thus giving the modules a higher CO2 footprint. Supply/offer "better" modules with lower footprint is not very high, may pose a risk to the energy transition.
Contradictory commercial interests and other interests.

The supply chain for PV currently largely takes place in China, with the US and EU only having a small fraction. If we keep purchasing affordable modules from China, developments towards more sustainable modules will remain limited. We may want to transition away from Si, in European project. Example of a different approach is Solarge, who make a plastic PV module. It may have a shorter lifespan compared to traditional, but it is a lot easier to process at EoL.

Panels can be sent to, e.g., Africa after their first use. However, that means they will end up as e-waste there as well, uncertain what happens after use. In NL, we have 'Stichting OPEN'.

Residual value in modules often very limited, contains some silver and other metals. Currently they're collected and transported to Belgium for processing, where they're crushed and often end up as filler materials in roads/construction. Must be aware that this material cannot be applied everywhere.

Challenges in policy and regulation; eco-design, materials passport, TUV-testing, environmental database, better processing at EoL, different materials and encapsulant.
Important for there to be a viable business case. Question of how to reward sustainable behaviour? Incentives? Working on a scorecard of PV modules, but not all criteria can be made public (manufacturers don't want all data to be public). And must be kept up to date.

Buyer Group helps with tender application/request texts, to determine the criteria for (public) procurement. Goal to scale this up to EU levels and to work with EU volumes. Send a clear signal to manufacturers; buyers want more than just cheap and high performance.

Product life extension options limited, often small-scale solutions. Question about the warranties (who is responsible for the second-life module? Installer may not want that responsibility when he cannot guarantee the quality long-term, especially for modules that he might not even know all that well). Reality is unruly.

APPENDIX M: Interview Notes PV Expert 6

TU Delft Expert on PV

PV contains lead and valuable materials, for those reasons you want to recycle them afterwards. On an example (the Boldz table) of product repurpose for PV, you have to consider partial shading. Older modules often don't have the best means for dealing with partial shading, that is an issue. Newer modules may adopt more bypass diodes to deal with partial shading.

Challenges

Challenge now is that of standardisation, cell size changed (+50% per decade over the last decades). Now we're reaching the upper limit to cell growth, as module sizes are determined by shipping container sizes. Reusing older modules with older, using smaller cells means having to compete with larger cells.

In manufacturing when the cell sizes get upgraded, so do the machines, and the old ones thrown out/replaced.

We now need around 1-4 TW of annual PV capacity manufacturing, growth rate to PV expected to end at end of decade. This manufacturing requires a lot of energy, but the energy pay-back time for PV is less than 2 years in most places, or even 1 year in Spain for example.

Last year ±10% of global silver production was used for the manufacturing of PV. Industry is lowering the use of silver in PV, but the reduction in materials use vs growth in capacity manufactured is not fast enough. Now they're investigating a switch to copper, which is in the evaluation-stage.

Cost share of a PV module in a system is now <50% of the total cost.

PV farms used to be planned for 2 inverter lifetimes, which was around 12-13 years, for the modules 25 years. Worked out as long as none of the inverters had an early defect.

EoL pathway for 20y old modules; recycling (on the material recovery level).

For 10y old panels Reuse may be feasible, depends on the specifics of the technology. When the first generation of PERC PV hits EoL, then Reuse is feasible. Helped when technological development slows down.

The business case for low-performance modules is difficult, since the installation costs remain. A solution to this could be an easy plug&play system for, e.g., use on balconies. To make it simple/easy enough for a user to do it themselves.

Modules from ±10y ago used around double the Si and 70% more silver compared to today's modules, can essentially make 2 new modules from 1 old module. The recycling business case also changes with the lower material-use in new PV tech. (less value to recover in raw material volumes)

Purity also plays a role; you want to recycle Si at 6N (99,9999%) or 9N (99,999999%) purity.

Other challenges; labelling of modules, you need to know what is in the panel; amount of valuable material. These are not always known until you open the module up.

Could have a QR on each module that links to a BOM from the manufacturer. In relation to intellectual property/company secrets, nowadays you can keep a company secret for up to ±1 year. With technology development at current pace, no need to keep your BOM secret for long. After 5-10 years there should be no earl reason to keep BOM secret.

Other challenge; logistics, the price per Wp is 5-10% logistics when importing from China. However, other costs are much higher in EU, so moving manufacturing here would not make it any cheaper. But you do need local recycling:

- *What can you pay in collection?*
- *Can you get enough volume to keep a factory running for ±50 weeks each year? (Now you'd run out after ± 4 weeks)*

Germany is currently the only place with relatively high volumes of PV waste, used to be around 10y ahead of the rest of EU. In installation not anymore since 2012 when subsidies got dropped.

PV Life Cycles

Multiple PV life cycles, possible but likely 30 years away, technological development needed. Glass Reuse should not be an issue. Frame would need their size standardised. For the cells, some material removal is okay, but sizes differ and are the doping levels also the same? (How much, how deep into the cell and what type of doping?) Gallium doping has less degradation, but for a long time there were patents on this doping type. Boron doping was used during that time, with faster degradation during use. Change needed at front end ±5-10 years, at back end may take 20-30 years. This is the time to be discussing alternatives to recycling, such as life extension.

On the Flowchart

Flowchart now starts with the discarded module, should perhaps start with the still functioning PV plant. Now, during disassembly of a plant, the removal of modules causes damage to the modules which can be avoided. There could be a service for disassembly/dismounting of the used modules and for transport, leading to more control over the quality. This combined with getting inverter data of the plant's performance over the last, e.g., year would be insightful and help find the best modules. (Or at least data from 1 sunny day).

In the flowchart, sort via visual inspection first, then a technical inspection if needed. (No need for technical inspection when the module is damaged beyond Repair). And some issues, such as broken/cracked cells are not always easy to see/spot; need for EL-testing. Does it still produce power in line with expectations? (Should be a guiding principle for the flowchart)