Strategies for circular end-of-life management of photovoltaic panels on Amsterdam rooftops

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By

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Mathijs Stokvisch

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EXECUTIVE SUMMARY

Over the past few years, the number of photovoltaic (PV) solar panels that are being installed in Amsterdam has been growing considerably. The amount of PV panel installations averages an annual growth of 50%, which is stimulated by the city its ambition to leave no roof unused by 2040. However, little attention is paid to what should happen with these PV panels once they reach end-of-life (EoL) and must be disposed of. This research aims to identify barriers and solution directions to upscale the circularity of EoL management for PV panels located in Amsterdam. This is done to collect better insights on what role cities can play to decrease the size of future PV waste streams. To accomplish this, the research goal is divided into three sub-goals. First, to estimate the size of future PV panel waste streams in Amsterdam over the period 2022-2050. Second, to enhance the understanding of the stakeholders involved in PV panel EoL management system and the barriers that hinder the implementation of innovative reuse and high-value recycling strategies. Third, to identify the ongoing socio-technical developments in the Netherlands to promote innovative reuse and high-value recyclng activities for EoL PV panels. The following research question is stated:

"What are the barriers and promising solution directions for circular end-of-life management of photovoltaic solar panels located in Amsterdam?"

The research question is answered by a mixed-methods approach. Primary data was collected via semi-structured interviews with actors involved in the system for PV panel EoL management. Secondary data was collected via document analysis, websites, and newspapers. The applied data analysis methods were quantitative analysis of PV panel waste streams in Amsterdam, stakeholder analysis of actors involved in PV panel EoL management, and interview data analysis.

The quantitative analysis results show that for Amsterdam to reach its goal to leave no roof unused by 2040, substantial increases are required in PV capacity in the coming 20 years. It is estimated that if the growth trend for PV panels installed in Amsterdam over the past five years linearly continues towards 2040, there is a deficit of 1.12 million panels to achieve the city its goal of leaving no roof unused. Based on the estimations for installed PV capacity, it is calculated that PV panel waste streams in Amsterdam will start to accumulate in 2031 and will substantially increase in size from 2037 onwards if an average lifetime of 20 years is applied. It is calculated that in 2031, the total mass of waste streams amounts to 170 tons, which will increase further to 8,863 tons in 2040 and will range between 27,366 and 36,477 tons by 2050. Glass is estimated to be the largest PV material waste stream, taking up 70% of the mass. Other PV material waste streams are aluminum (15%), polymers (10%), silicon (5%) and silver (0,1%). While silver only presents 0,1% of the volume, it accounts for roughly 65% of the material value, and accumulates to a material value of 17.8-23.8 million euros by the year 2050.

The results also indicate that cities currently do not play a significant role in the system for PV EoL management. Instead, the collection and processing of EoL PV panels is organized as a national system, where the organization of extended user responsibility (EPR) plays a crucial role. Since the 1st of March 2021, Stichting OPEN is appointed as the responsible actor for execution of EPR on behalf of all producers in the Netherlands. Stichting OPEN enforces EPR by charging removal fees to PV panel producers and uses these funds to contract collection points and collection companies, and to set up contracts with recyclers. Obsolete panels are currently collected by individual contractors and exported to foreign recycling facilities in Belgium or Germany. In these recycling facilities, most PV panels are pulverized into low-grade building materials or used as fuel in incinerators.

Multiple barriers that interact to form lock-in around existing and unsustainable technologies for PV EoL management are identified. Infrastructure and technological barriers reside in that upcycling technologies find it difficult to compete with low-value recycling activities due to issues of scale. This is also due to the use of ethylene vinyl acetate (EVA) encapsulation in contemporary PV panel design, which promotes durability and lifetime but hinders product recyclability. Also, PV panels are currently not labeled, which decreases the efficiency of recycling processes. Organizational barriers stem from the organization of EPR, specifically from disposal fees. The current size of disposal fees is far from sufficient to facilitate high-quality recycling activities for PV panels, which is stimulated by a lack of future accountability in the EPR finance mechanism. Institutional barriers reside in recycling targets that are based on weight instead of value. This demotivates incentives to change the existing system, as PV panel producers and recyclers are already complying with WEEE standards for minimum recycling percentages. Another institutional barrier is the design of subsidy grants. These tend to focus on generation capacity instead of PV panel circularity, which stimulates the replacement of PV panels based on economical rather than technical lifetime. Supply-chain-related barriers stem from the lack of collaboration throughout the PV supply chain. It is suggested that there is both a lack of collaboration between PV panel manufacturers and PV panel recyclers and competition between WEEE collection parties. Economical barriers reside in that product price, instead of product sustainability, is considered a key factor for PV panel procurement along with product lifetime and production capacity. Also, the quantities of returning PV panels are currently too low for upcycling technologies to be considered economically feasible. Lastly, the use of EVA encapsulant in panel design also hinders cost-effective upcycling

It is suggested that an increase in PV circularity at EoL is inextricably linked to the earlier phases of the PV supply chain. Therefore, multiple innovations and practices are identified along the PV supply chain in the Netherlands that have the potential to overcome the identified barriers. These developments involve a broad range of actors, ranging from PV panel manufacturers, users, and producers to public authorities. The most interesting technological developments to increase PV panel circularity focus on circular PV panel design, material passports, and implementation of upcycling technologies. Here, the choice for circular PV panels can be stimulated via sustainable procurement criteria, while implementation of upcycling technologies can be stimulated by increasing PV panel disposal fees. However, these types of developments become less relevant when the city-scale is considered, as cities are found to be predominantly concerned with the PV panel user phase. The research findings indicate that opportunities to increase PV circularity in cities reside in experimentation with local reuse initiatives. Experimentation with local reuse is a promising circular strategy to promote PV panel life-length and has the potential to broaden the access to sustainable energy. Here, it is especially interesting to look for collaborations with large-scale PV panel installations. As PV panels in these types of installations are more likely to be replaced based on economic lifetime and financial returns, which increases the reuse potential of the removed PV panels. Furthermore, local reuse initiatives provide a promising context for experimentation with reuse-based business models and can facilitate learning practices.

While the present conditions are found to create windows of opportunity for modification of the existing system via the identified solution directions, external intervention is also required. A future model for PV EoL management is ultimately shaped by the overall aim and visions of the stakeholders involved. System transformation depends highly on the aim of these stakeholders, which is to create business and economic value or include more societal and environmental aspects into their vision for PV panel end-of-life management. In the case of Amsterdam, this translates to the willingness of the city to combine its energy transition with its circular economy ambitions by empowering initiatives that combine both ambitions and support a circular energy transition.

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LIST OF ABBREVIATIONS

BIPV	-	Building Integrated Photovoltaics
CBAM	-	Carbon Border Adjustment Mechanism
CE	-	Circular Economy
CdTe	-	Cadmium Telluride
CIRCUSOL	-	Circular Business Models for the Solar Power Industry
c-Si	-	Crystalline Silicon
DfR	-	Design for Recycling
EoL	-	End-of-life
EPEAT	-	Electronic Product Environmental Assessment Tool
EPR	-	Extended Producer Responsibility
EU	-	European Union
EVA	-	Ethylene vinyl acetate
MLP	-	Multi-level perspective
MW	-	Megawatt
PARSEC	-	PV and Recycling for lead-free PV panels
PFAS	-	Per- and polyfluoroalkyl substances
PV	-	Photovoltaic
R&D	-	Research and Development
SNM	-	Strategic Niche Management
SSI	-	Semi-structured interviews
WEEE	-	Waste Electrical and Electrical Equipment
Wp	-	Watt peak

1. INTRODUCTION

Over the past few years, the number of photovoltaic (PV) panels that are being installed in Amsterdam has been growing considerably. The amount of PV panel installations averages an annual growth of 50%, which is stimulated by the city its ambition to leave no roof unused by 2040 (Programmateam Amsterdam Klimaatneutraal, 2020). However, little attention is paid to what should happen with these panels once they reach end-of-life and must be disposed of. The yearly amount of decommissioned PV panels in the Netherlands is approximately 0.2% compared to new installations in the same year (WEEE register, 2020). However, it is expected that PV panel waste streams will already start to become problematic by 2030-2035 (Beeftink & Bergsma, 2021). Broken or obsolete PV panels in the European Union (EU) and therefore also in the Netherlands fall under the legislation for waste electronic and electronic equipment (WEEE). One of the most important consequences of the WEEE directive is the principle of extended producer responsibility (EPR). Based on EPR, manufacturers and importers that put electronic equipment on the market must ensure a system that collects and recycles these products when they reach the end of their lifetime. In 2016, an average of 45% of all electronic waste in the Netherlands was collected for recycling. The Dutch government intends to increase this to 85% in the coming years (Beeftink & Bergsma, 2021). Collected PV panels are currently recycled into lower-grade materials due to the absence of environmentally and economically effective infrastructure and technologies (Sica et al., 2018). This makes it likely that substantial amounts of scarce PV materials, such as silver, will be lost. The loss of these so-called critical materials is stated to be a growing risk for envisioned Dutch energy transition (van Exter et al., 2021).

1.1 PROBLEM STATEMENT

The above-mentioned developments imply that the substantial growth of PV installations in Amsterdam is inevitably linked to a loss of valuable materials in the absence of circular end-of-life (EoL) management (Sinke et al., 2021). Next to an unnecessary loss of PV materials, this also creates tensions between the city its ambitions to become both climate neutral and completely circular by 2050 (Gemeente Amsterdam, 2020). The increase in PV panel waste streams will be mainly caused by the first generation of installed PV panels that reach the end of their lifetime (Kerp & Jönsthövel, 2021). Additionally, e-waste will also be generated by the replacement of relatively new PV panels (<10 years) in favor of more efficient and cheaper panels (Duran et al., 2022). It seems to be a challenge for Amsterdam to meet its objectives to become both climate neutral and completely circular if the contemporary practices for PV panel EoL management are persisted. The systematic literature review (Chapter 2) provides interesting insights on how reuse and recycling strategies can enhance the circularity of PV panel EoL management. However, there are still multiple knowledge gaps identified in the literature reviewed concerning the implementation of these strategies (see Section 2.2.3). It is found that additional research is required on the conditions that must be met to make high-value recycling methods competitive with contemporary recycling practices. Here, it is interesting to include social-technical aspects that focus on the interaction between stakeholders involved in PV EoL management. Moreover, there is also a need for further research on how policies can be improved and implemented to manage emerging PV waste streams. Additionally, it is still unsure under what conditions PV panel reuse can complement PV recycling and how to make PV panel reuse more attractive for consumers in general.

1.2 RESEARCH GOAL AND RESEARCH QUESTION

This research aims to identify barriers and solution directions to upscale the circularity of EoL management for PV panels in Amsterdam. This is done to fill the identified knowledge gaps and enhance the understanding on what role cities can play to decrease the size of future PV waste streams. To accomplish this, the research goal is divided into three sub-goals. First, to estimate the size of future PV panel waste streams in Amsterdam over the period 2022-2050. Second, to enhance the understanding of the stakeholders involved in the PV panel EoL management system and the barriers that hinder the implementation of innovative reuse and high-value recycling strategies. Third, to identify the ongoing socio-technical developments in the Netherlands to promote innovative reuse and high-value recyclng activities for EoL PV panels. The following research question is stated:

RQ: WHAT ARE THE BARRIERS AND PROMISING SOLUTION DIRECTIONS FOR CIRCULAR END-OF-LIFE MANAGEMENT OF PHOTOVOLTAIC SOLAR PANELS LOCATED IN AMSTERDAM?

To answer the main research question, the following sub-research questions (SRQs) are formulated:

- SRQ1: What is the estimated size of photovoltaic panel waste streams in Amsterdam for the period 2022-2050?
- SRQ2: How is the system for end-of-life management of photovoltaic panels currently organized?
- SRQ3: What are barriers to circular photovoltaic panel end-of-life management?
- SRQ4: What are promising niche-level developments and practices in the Netherlands to upscale circular end-of-life activities for photovoltaic panels?

1.3 OUTLINE OF REPORT

The report is structured as follows. In chapter 2, the methodology and results of the systematic literature review are shown. This chapter provides an overview of both the existing research on circular strategies for PV panel EoL management and the identified knowledge gaps. Chapter 3 sets out the theoretical and conceptual framework for this research. Chapter 4 explains the research approach, research design, and applied methods. Chapter 5 presents the quantitative analysis results on PV panel waste streams in Amsterdam for the period 2022-2050. Chapter 6 provides the stakeholder analysis results for the PV panel EoL management system and identifies barriers to increase PV panel circularity. Chapter 7 presents the results of the ongoing developments in the Netherlands to increase PV panel circularity. Chapter 8 discusses the applicability of the applied theories, the research findings in relation to existing literature, the research limitations, and the implications for knowledge users. Finally, chapter 9 concludes this research by answering the research questions and provides recommendations for future research.

2. LITERATURE REVIEW ON CIRCULAR ECONOMY STRATEGIES FOR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

2.1 LITERATURE REVIEW METHODOLOGY

A systematic literature review to identify circular economy (CE) strategies for PV panel EoL management was conducted based on four steps: identification, screening, eligibility, and inclusion (Figure 2.1). The goal of the literature review was to provide an overview of existing research on PV panel EoL management and to identify knowledge gaps for this research to address.

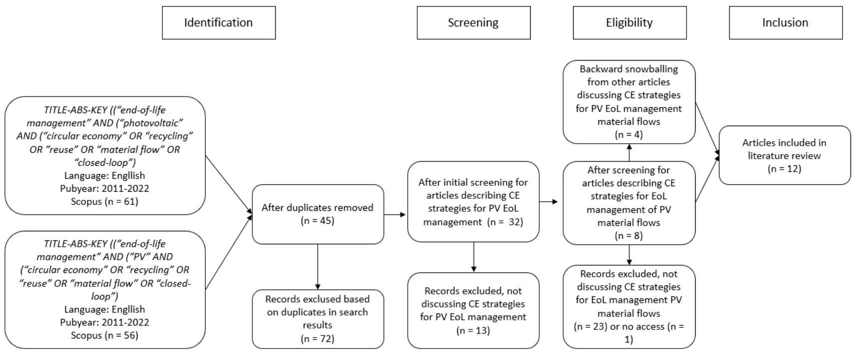

FIGURE 2.1. CONCEPTUAL OVERVIEW OF LITERATURE SELECTION METHODOLOGY FOR REVIEW

Relevant articles were identified in Scopus using the keywords “EoL management”, “photovoltaic”, “PV”, “circular economy”, “recycling”, “material flow”, “reuse” and “closed-loop”. These keywords were selected based on the scanning of article abstracts and were combined in multiple ways (Table 2.1). The review included papers written in English during the last ten years (2012-2022) to account for technological advances and to increase awareness of the aspect of PV panel circularity. This timeframe was also chosen since research on PV panel EoL management increased considerably from 2010 onwards (Salim et al., 2019). The following Boolean operator was used in Scopus: *TITLE-ABS-KEY ((“end-of-life management” AND (“photovoltaic” OR “PV”) AND (“circular economy” OR “recycling” OR “reuse” OR “material flow” OR “closed-loop”)*. In total, the identification step resulted in 45 articles.

TABLE 2.1. KEYWORDS AND HITS IN THE IDENTIFICATION STEP

Year	1st search term	2nd search term	3rd search term	Number of hits
2011-2022	end-of-life management	photovoltaic	circular economy	9
2011-2022	end-of-life management	photovoltaic	material flow	3
2011-2022	end-of-life management	photovoltaic	recycling	43
2011-2022	end-of-life management	photovoltaic	reuse	2
2011-2022	end-of-life management	photovoltaic	closed-loop	4
2011-2022	end-of-life management	PV	circular economy	9
2011-2022	end-of-life management	PV	material flow	2
2011-2022	end-of-life management	PV	recycling	39
2011-2022	end-of-life management	PV	reuse	2
2011-2022	end-of-life management	PV	closed-loop	4
			Total	117
			Duplicates	72
			Final	45

After step 1, identified articles were screened for eligibility using two criteria. First (1), included studies must be predominantly concerned with CE strategies for PV panels. Second (2), the CE strategies that were described in the studies must be related to EoL management of PV panels or PV panel material flows. The articles were scanned for eligibility by reading titles, abstracts, and keywords and resulted in a remaining number of 8 articles. Additionally, backward snowballing was applied to make sure to involve relevant papers that would otherwise have been left out based on the used criteria (Wee & Banister, 2016). This resulted in an additional inclusion of 4 articles and a total number of 12 articles reviewed (Table 2.2).

TABLE 2.2. OVERVIEW OF SELECTED ARTICLES

Author(s)	Year of publication	Journal	Cited by
Sica, D., Malandrino, O., Supino, S., Testa, M., Lucchetti, M.C.*	2018	Renewable and Sustainable Energy Reviews	68
Deng, R., Chang, N.L., Ouyang, Z., Chong, C.M.	2019	Renewable and Sustainable Energy Reviews	94
Salim, H.K., Stewart, R.A., Sahin, O., Dudley, M.	2019	Journal of Cleaner Production	60
Farrell, C.C., Osman, A.I., Doherty, R., (...), Al-Muhtaseb, A.H., Rooney, D.W.	2020	Renewable and Sustainable Energy Reviews	31
Tsanakas, J.A., van der Heide, A., Radavičius, T., (...), Poortmans, J., Voroshazi, E.	2020	Progress in Photovoltaics: Research and Applications	24
Mahmoudi, S., Huda, N., Behnia, M.	2021	Journal of Cleaner Production	6
van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J., Voroshazi, E.	2021	Progress in Photovoltaics: Research and Applications	0
Walzberg, J., Carpenter, A., Heath, G.A.	2021	National Renewable Energy Laboratory	0
Radavičius, T., van der Heide, A., (...), Denafas, J., & Tvaronavičienė, M*	2021	Insights into Regional Development	5
Franco, M.A., Groesser, S.N.*	2021	Sustainability	3
Ganesan, K., Valderrama, C.	2022	Energy	0
Ovaitt, S., Mirletz, H., Seetharaman, S., Barnes, T.*	2022	iScience	0

*Included by backward snowballing

2.2 LITERATURE REVIEW RESULTS

In recent years, CE strategies for PV panels are increasingly discussed as an alternative to the current linear "take-make-consume-waste" model (Salim et al., 2019; Sica et al., 2018). This is mainly caused by the large number of PV panels that will reach the EoL stage within the coming 5 to 10 years (Deng et al., 2019; Farrell et al., 2020; Salim et al., 2019). However, many of the technologies relating to CE strategies for sustainable EoL management of PV panels are still being developed (Deng et al., 2019; Radavičius et al., 2021). As a result, most of the obsolete PV panels are currently incinerated or landfilled (Deng et al., 2019). Landfilling allows toxic materials, such as lead, to enter the soil (Salim et al., 2019). Additionally, both incineration and landfill result in an overall loss of precious and scarce materials and lead to highly negative environmental and health impacts (Deng et al., 2019; Mahmoudi et al., 2021; Salim et al., 2019).

In the review, two types of literature were identified: (1) literature reviews on CE strategies for EoL management of PV panels and (2) CE strategies as methods for sustainable EoL management of PV panels and their materials. The categorization of reviewed articles is shown below (Table 2.3).

TABLE 2.3. CATEGORIZATION OF SELECTED ARTICLES

Category	**Description**	**References**
(1) Literature reviews on circular economy strategies for end-of-life management of photovoltaic PV panels	Articles that analyze, evaluate, and discuss the current state of literature concerning circular economy strategies for end-of-life management	(Deng et al., 2019; Farrell et al., 2020; Franco & Groesser, 2021; Salim et al., 2019; Sica et al., 2018; Tsanakas et al., 2020)
(2) Circular economy strategies as methods for sustainable end-of-life management of photovoltaic PV panels	Circular economy strategies are applied, evaluated, and discussed as sustainable methods for end-of-life management of photovoltaic PV panel materials	(Ganesan & Valderrama, 2022; Mahmoudi et al., 2021; Ovaitt et al., 2022; Radavičius et al., 2021; van der Heide et al., 2021; Walzberg et al., 2021)

After the categorization of the selected articles, the literature review provided an overview of implemented and under-research CE strategies for PV panel EoL management. It was found that CE strategies in general are most often described in accord with the 3R principle of reducing, reusing, and recycling (Salim et al., 2019; Sica et al., 2018). Here, CE strategies for EoL management were found to be predominantly concerned with recycling. More specifically, recycling of crystalline silicon (c-Si) PV panels, with a lesser focus on thin-film panels, such as CdTe (Farrell et al., 2020). This is understandable given that c-Si PV panels represent over 90% of the current market share (Sica et al., 2018). Thus, the large majority of PV panels that will reach EoL in the coming decade will be c-Si. Also, it was found that shorter-lived panels account for 81% more waste, which stimulates the need for more efficient life-extension strategies (Ovaitt et al., 2022). Identified reuse strategies involve direct reuse, repair, refurbishment, remanufacture, and repurposing. Lastly, reduction strategies were barely mentioned. This is understandable given that the selected articles were mainly concerned with PV panel EoL management. While reduction strategies, consisting of refuse, rethink, and reduce, are especially relevant during the design and production stages. An overview of identified CE strategies for PV EoL management and their descriptions is shown in Table 2.4. In the next sections, the identified strategies and knowledge gaps for further research are discussed.

TABLE 2.4. OVERVIEW OF IDENTIFIED CIRCULAR ECONOMY STRATEGIES FOR END-OF-LIFE MANAGEMENT OF PHOTOVOLTAIC PANELS

Circular economy strategy	Specific strategy	Description	Reference
Reuse	Direct re-use	Extend lifetime through direct re-use.	(Tsanakas et al., 2020; van der Heide et al., 2021; Walzberg et al., 2021)
	Repair	Extend lifetime through repairment	(Radavičius et al., 2021; Salim et al., 2019; Tsanakas et al., 2020; van der Heide et al., 2021; Walzberg et al., 2021)
	Refurbish	Extend lifetime through refurbishment	(Radavičius et al., 2021; Salim et al., 2019; Tsanakas et al., 2020; van der Heide et al., 2021; Walzberg et al., 2021)
	Remanufacture	Use discarded PV panel or parts of it in a new product with the same function	(Deng et al., 2019; Farrell et al., 2020; Radavičius et al., 2021; Salim et al., 2019; Tsanakas et al., 2020; Walzberg et al., 2021)
	Repurpose	Use discarded PV panel or parts of it in a new function	(Radavičius et al., 2021)
Recycle	Upcycling	Using either mechanical, thermal, or chemical processes to realize upcycling of PV panel materials.	(Deng et al., 2019; Franco & Groesser, 2021; Ganesan & Valderrama, 2022; Ovaitt et al., 2022; Sica et al., 2018)
	Downcycling	Extract materials from PV panels that have a lower value and must be used elsewhere	(Deng et al., 2019; Farrell et al., 2020; Franco & Groesser, 2021; Salim et al., 2019)

2.2.1 REUSE STRATEGIES

So far, insights from the literature concerning EoL management of PV panels have been rather fragmented and one-sided and predominantly focus on recycling processes and innovation efforts (Tsanakas et al., 2020). However, several strategies to reuse PV panels were identified in the reviewed literature. These are divided into strategies for extending the lifetime of the PV panel to be reused in the same function (reuse, repair, refurbish), remanufacturing PV panels or parts of it in a new product with the same function, and repurposing PV panels or parts in a new product with a different function.

Lifespan extension of PV panels via reuse activities is considered to be quite complex in high income countries. As a result, many second-hand PV panels are being shipped to developing countries where proper recycling facilities are lacking, which creates an outflow of valuable materials and risks of improper disposal in the long term (van der Heide et al., 2021). According to van der Heide et al. (2021), this complexity is caused by technical, economic, environmental, and legislative requirements. Technical requirements for reusing PV panels concern whether a PV panel can be directly reused, repaired, or refurbished for reuse or not (Walzberg et al., 2021). Here, a threshold module performance of 70% compared to its original performance and absence of safety concerns is advised (van der Heide et al., 2021). Also, the expected lifetime should be long enough to make the reuse worthwhile. According to Tsanakas et al. (2020), especially the economic and environmental value of PV panel reuse are still relatively unexplored. As a result, knowledge of best practices for repair, refurbishment, and the reliability and qualification of second-hand PV panels has been scarce (Tsanakas et al., 2020). Reuse of a PV panel should be financially attractive and investors should have enough trust in reused module reliability even though product warranties for second-hand panels are currently limited to non-existent

(van der Heide et al., 2021). Salim et al. (2019) find that the current lack of economic incentives to reuse EoL PV panels is driven by low manufacturer and consumer confidence in remanufactured products. Increasing demand is crucial, given that insufficient demand for second-hand modules results in sending them to the cheapest EoL option available (Walzberg et al., 2021). Thus, there is a growing need for appropriate business models, such as leasing, sharing, or creating warranties, to change the general perception and promote reuse strategies (Salim et al., 2019). In terms of environmental benefits, reuse is very appealing because it requires fewer resources, less energy, and less labor compared to the production of new products from raw materials. In some cases, reuse can be even more appealing in terms of these factors compared to recycling and disposal (Tsanakas et al., 2020). Given that life extension generally has no negative environmental effects, this strategy could also be used to give recycling methods time to improve (van der Heide et al., 2021). However, limited research has been conducted so far on PV panel reuse due to the long operational lifespan of >20 years (Tsanakas et al., 2020). Radavičius et al. (2021) find that the lack of traceability of panels and their materials impacts their reusability since this lack of information hinders second-use value. Additionally, the diversity of operational panel components and their materials require evaluation for second-hand markets (Radavičius et al., 2021). From a legislative point of view, there should be a clear set of requirements for reusing modules to avoid abuse or misuse around the concept of “PV panel reuse”. Given these requirements, van der Heide et al. (2021) find that for high-income countries, the reuse of PV panels within the same function is currently only interesting in three cases: (1) to replace all PV panels in an existing plant to extend plant lifetime at a lower cost, (2) to repower underperforming PV systems and (3) to remanufacture parts of second-hand PV panels in new modules.

Furthermore, Radavičius et al. (2021) do not identify remanufacturing and repurposing as relevant reuse strategies for PV panels. The remanufacturing capacity of solar cells in the EU was found to be only 0.2 % compared to the world its producer capacity in 2019 (Radavičius et al., 2021). This can be explained by the lack of adequate infrastructure for second-hand components or products due to the low amount of reuse, repair, and remanufacture activities and vice-versa (Radavičius et al., 2021). Also, Farrell et al. (2020) find that due to the contemporary design of c-Si PV panels, using lamination and EVA encapsulation techniques, opportunities for repair and maintenance, reuse of individual components, and remanufacturing of solar cells without aggressive processing are very limited.

2.2.2 RECYCLE STRATEGIES

In accord with Tsanakas et al. (2020), existing academic literature on CE strategies for PV panels is predominantly concerned with recycling. This is understandable given that the increase in PV panel waste flows will mostly be linked to c-Si PV panels. C-Si PV panels represent >90% of the current market share, while they are considered economically unattractive for recycling (Sica et al., 2018). For example, current recycle revenues for PV panels are two magnitudes lower compared to smartphones due to the low concentrations of recoverable material and its value (Deng et al., 2019). Therefore, it is essential to develop commercially viable strategies and technologies for EoL PV panel recycling (Deng et al., 2019). In the literature reviewed, recycling strategies can be divided into strategies for downcycling and upcycling.

Downcycling refers to the extraction of materials out of PV panels that are contaminated and that therefore cannot be reused in the same function and have to be used elsewhere (Deng et al., 2019). Downcycling is stimulated by contemporary PV panel design. Contemporary PV panels often have an EVA encapsulation layer, which makes it difficult to remove or delaminate the glass from the solar cells (Salim et al., 2019). As a consequence, downcycling activities are concerned with the low-value recycling of glass and aluminum frames (Deng et al., 2019). These are either sold for commodity prices after mechanical removal or put in general aluminum and glass recycling routes (Farrell et al., 2020). Since glass constitutes more than 75% of the material, glass recyclers attempt to recycle PV panels by using existing flat-glass recycling lines. This involves the manual movement of the frame, junction box, and copper cables, followed by shredding, crushing, and a series of manual and mechanical sorting and extraction processes (Deng et al., 2019). According to Deng et al. (2019), glass recycling appears to be economically feasible when landfill fees are high or when landfill of PV panels is prohibited. However, the implementation of glass recycling is not yet widespread since the required volume of discarded PV panels is not always sufficient for glass recycling to be economically feasible (Franco & Groesser, 2021). Additionally, Additionally, glass recycling is also hindered by material impurities due to the EVA encapsulation layer (Deng et al., 2019).

Upcycling refers to the high-value recycling of all PV panel components. This can be accomplished by implementing more complex recycling processes (Deng et al., 2019). However, most R&D funds in the PV industry aim to improve the efficiency of c-Si panels, while less effort is paid to research cost-effective and innovative processes for PV panel recycling at EoL (Franco & Groesser, 2021). Deng et al. (2019) identify multiple promising technologies for upcycling EoL PV panels based on delamination and solar cell recycling techniques. Delamination techniques entail a clean separation of the glass and solar cells. After delamination, solar cells can be recycled in such a way that silicon and metals are separated (Deng et al., 2019). Three methods for delamination are distinguished: mechanical, thermal, and chemical delamination. Respectively, these methods entail the separation of module layers using mechanical processes, thermal decomposition of the encapsulation layer, and dissolving of the encapsulation layer through applying (in)organic solvents (Deng et al., 2019). In general, mechanical processes, such as shredding and hammer milling, are seen as less time and energy consuming but result in relatively lower material quality after recycling due to material size and contamination. While for chemical and thermal processes this is the other way around. However, methods can be combined to obtain better results (Deng et al., 2019). Currently, these technologies are still under development and are facing profitability issues due to the low volumes of discarded PV panels that are currently available (Franco & Groesser, 2021). Costs here are mainly associated with the collection, dismantling, transportation, and capital costs (Deng et al., 2019). Low volumes not only make recycling activities more expensive but also negatively affect manufacturer incentives to proactively engage in recycling schemes (Franco & Groesser, 2021). This results in an underdeveloped upcycling infrastructure due to the limited implementation of high-value recycling technologies. However, it is expected that the growing number of PV panels that will reach EoL will encourage the implementation of high-value recycling technologies in the coming decade (Deng et al., 2019). According to Ganesan and Valderrama (2022), successful implementation of upcycling technologies and establishing an upcycling infrastructure in general, requires lowering of processing costs via upscaling, economic incentives, or regulatory instruments. Additionally, Mahmoudi et al. (2021) find that there is a strong potential for a CE for PV panels if an environmentally friendly pathway could be achieved for PV panel recycling that allows for material purities to reach the market demand. However, implementation of a CE for PV panels requires proper marginalization at the management levels (Mahmoudi et al., 2021). Following this line of reasoning, Sica et al. (2018) find that the growing amount of PV panel waste presents unique opportunities for creating value via economic incentives, such as job creation and setting up local businesses. Furthermore, cooperation between the parties involved from production to recycling is essential to facilitate a closed-loop for PV panel materials and maximize economic and environmental benefits (Deng et al., 2019).

2.2.3 KNOWLEDGE GAPS FOR THESIS RESEARCH

This section will conclude the literature review by setting-out the identified knowledge gaps in the reviewed literature. It is found that academic literature on CE strategies for PV panel EoL management is predominantly concerned with the recycling of c-Si (and to a lesser degree CdTe) PV panels and often does this from a technological standpoint. It is found that promising technologies for PV panel recycling are already being developed, which are based on mechanical, thermal, and chemical processes. However, implementation of these technologies requires higher volumes of EoL PV panels to become economically feasible. Given that significantly higher volumes of decommissioned PV panels will start to occur in the coming decade, it can be expected that recycling technologies and infrastructure will also be able to upscale. However, additional research is required on the conditions that must be met to make high-value recycling methods competitive with contemporary recycling practices (Deng et al., 2019). This also requires collaboration between the stakeholders involved in the PV industry. Therefore, future research is also required on a more social perspective on PV EoL management, which focuses on the interactions between individual actors or segments in the PV value chain (Deng et al., 2019). This can provide a more holistic view on barriers and opportunities for circular PV EoL management and the PV industry in general (Franco & Groesser, 2021). Furthermore, there is also a need for future research on how policies can be improved and implemented to manage emerging PV waste streams (Ganesan and Valderrama, 2022). This is required to ensure a reliable and sustainable recycling procedure, which maximizes resource efficiency.

Despite the predominant focus in the academic literature on recycling technologies, this CE strategy is generally seen as less sustainable compared to reuse strategies in terms of environmental impact. To create a CE for PV panels, it is therefore crucial to also adopt more innovative reuse strategies in the future. However, the literature review results pointed out that for high-income countries, implementation of reuse strategies is still quite complex. Therefore, it is unsure what appropriate business models for PV panel reuse will look like (Salim et al., 2019). Also, there is a need for additional research on how to make PV panel reuse more attractive and promote consumer confidence in reused or remanufactured products (Salim et al., 2019). Moreover, it is found to be still unsure under what conditions PV panel reuse can complement or provide an alternative to PV recycling (van der Heide et al., 2021).

The following chapter will set out the theoretical and conceptual frameworks that are applied in this research.

3. THEORETICAL BACKGROUND

3.1 THEORETICAL FRAMEWORK

The theoretical framework places PV panel EoL management in the context of socio-technical system theory. First, PV panel EoL management is described as a socio-technical system. Hereafter, the multi-level perspective framework is introduced to explain transition dynamics in socio-technical systems. Hereafter, strategic niche management theory is introduced to explain how niches can function as steppingstones for setting about broader societal change and sustainable development.

3.1.1 PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT AS A SOCIO-TECHNICAL SYSTEM

Socio-technical systems encompass the production, diffusion, and use of technology and are defined in terms of functional linkages between elements that are necessary the fulfill societal functions (Geels, 2004). Societal functions refer to the specific functions of society that are performed through interaction between the different elements in the system (Markard et al., 2012). Socio-technical systems do not only include the technological infrastructure that is required to fulfill a societal function but also the actors, networks, and institutions that provide services related to the technology (Geels, 2004). Socio-technical systems do not operate autonomously. Rather, their functioning is the outcome of the interaction and activity of human actors (Geels, 2004). Human actors are in turn embedded in different social groups that share similar characteristics, such as roles and responsibilities (Figure 3.1).

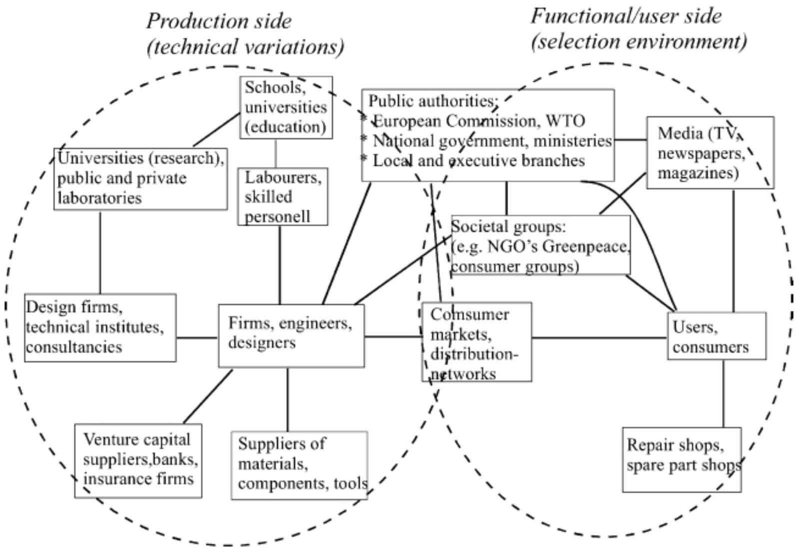

FIGURE 3.1. SCHEMATIC OVERVIEW OF TYPES OF SOCIAL GROUPS THAT OPERATE IN SOCIO-TECHNICAL SYSTEMS (GEELS, 2004)

Management of end-of-life PV panels forms a good example of a complex socio-technical system as it involves interactions between people and technology to achieve a certain purpose. Moreover, the system involves multiple stakeholders, each with their interests, along with an institutional framework, collection and treatment technologies, and interaction between these factors that connect them (Zacho et al., 2018). In the case of contemporary European WEEE management, the utilization of linear and destructive technologies has become the standard (Cole et al., 2019). In response, the European WEEE directive and the updated EU circular economy plan have been developed. Both are considered key instruments for EU members to support the transition towards more sustainable and circular management for end-of-life electronic equipment (Aminoff & Sundqvist-Andberg, 2021). The European WEEE directive uses a waste hierarchy (Figure 3.2), which prioritizes the prevention of waste, followed by reuse, recycling, and other types of waste recovery (Andersson et al., 2019). Based on the WEEE directive, manufacturers and producers are held responsible for the life cycle impacts of their products through the principle of extended user responsibility (EPR). EPR is a modern version of the polluter pays principle that states that the costs of disposal and recovery must be transferred to the producers (Ghisellini et al., 2016). However, it is found that WEEE targets are mainly met through low-value recycling activities (Zacho et al., 2018).

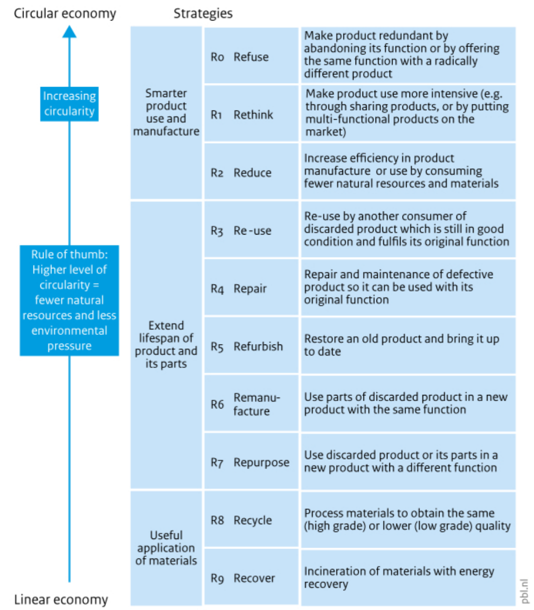

FIGURE 3.2 WASTE HIERARCHY IN ACCORD WITH R-LADDER IN THE NETHERLANDS. SOURCE: POTTING ET AL. (2016)

The next section will further elaborate on this notion by introducing the multi-level perspective framework to explain path-dependencies and lock-in around certain technologies within socio-technical systems.

3.1.2 THE MULTI-LEVEL PERSPECTIVE FRAMEWORK

The multi-level perspective (MLP) framework has been developed to help explain path-dependencies and lock-in within existing socio-technical systems around certain technologies (Geels, 2007; Loorbach et al., 2017). The MLP views transitions as non-linear processes that are the result of the interplay between developments at three systemic levels: niches, socio-technical regimes, and the socio-technical landscape (Figure 3.3).

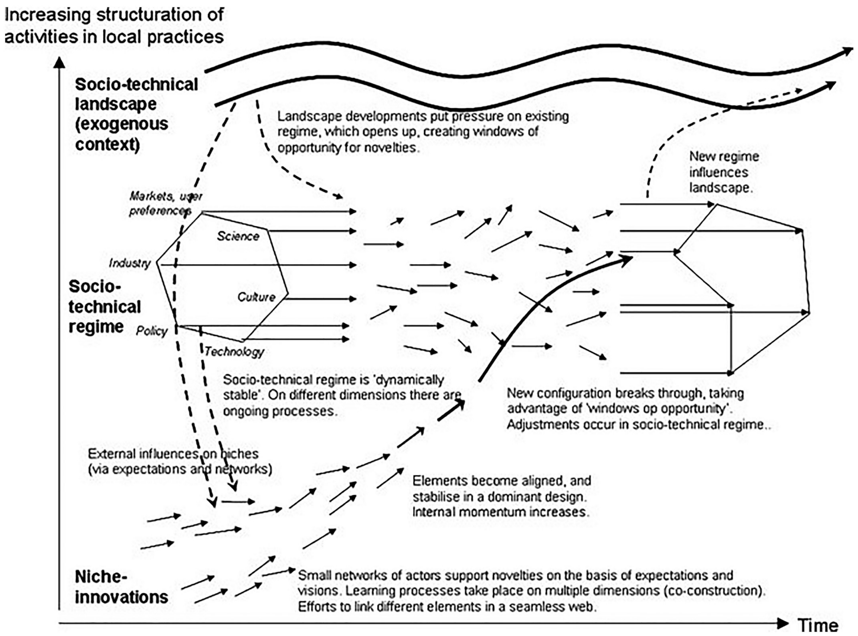

FIGURE 3.3. THE MULTI-LEVEL PERSPECTIVE ON TRANSITIONS (GEELS & SCHOT, 2007)

Socio-technical regimes can be characterized as the existing practices and associated rules that stabilize the existing socio-technical system (Geels, 2011). A regime can thus be conceptualized as the 'normal way' of doing things, wherein certain technologies are dominant (van Eijck & Romijn, 2008). A socio-technical regime results from linkages of rules between different sub-regimes. These are defined by Geels (2004) as technology, market and user preferences, industry, science, policy, and culture. Due to the interaction and co-evolution of trajectories within these sub-regimes, socio-technical regimes are characterized by lock-in. Lock-in results from co-evolutionary processes among technical infrastructures, organizations, society, and governing institutions, which creates mismatches between innovative developments and the regime (Unruh, 2002). This creates self-reinforcing barriers that hinder or slow down transformation (Aminoff & Sundqvist-Andberg, 2021). For example, the absence of appropriate infrastructure (Loorbach et al., 2017). In a socio-technical analysis of the Danish WEEE management system, Zacho et al. (2018) identify three types of barriers to circularity: technological, organizational, and institutional. While in their analysis of the Finnish WEEE management system,

Aminoff and Sundqvist-Andberg (2021) identify five categories: infrastructure and technological, organizational, institutional, supply chain, and economic.

Niches are seen as protected spaces, such as subsidized demonstrations or R&D projects, wherein users are willing to support emerging innovations and are therefore important for sustainability transitions (Geels, 2004). Innovation is not seen as a straightforward process due to the presence of multidimensional barriers and therefore requires interrelated technological and social change (Raven et al., 2010; Schot & Geels, 2008). The concept of niches is often used positively as a counterpart to issues that occur on the regime level (Raven et al., 2010). This is because, in the MLP, niches are the location wherein radical innovations are developed, which can grow and destabilize or even change regime practices (Geels, 2011). This is not easy due to the mismatches between niche-level innovations and existing regime dimensions (Geels, 2011). Therefore, innovative technologies can best be described as '*hopeful monstrosities*' (Schot and Geels, 2008: p 537). 'Hopeful' refers to how innovative technologies, including both products and processes, can have a promising future, but they are also 'monstrous' since emerging technologies perform crudely within the existing regime due to the lock-in mechanisms. As a result, emerging technologies cannot directly compete against established technologies. This is a central issue for many emerging technologies with sustainability promises (Geels, 2011).

The sociotechnical landscape is the wider context in which regimes are embedded and therefore influences the dynamics that happen on the regime and niche levels. It consists of the ideas, ideologies, societal values, and macro-economic and political patterns that sustain society (Geels, 2004). These represent a varied set of material and immaterial factors which cannot be altered via the regime and niche level in the short run (Geels & Schot, 2007). However, sudden or unexpected large-scale events can emerge from the landscape, such as crises (van Eijck & Romijn, 2008).

The next section will further elaborate on the role of niche-level actors as incubators of innovation and will introduce strategic niche management theory.

3.1.3 NICHE-LEVEL INNOVATIONS AS DRIVERS OF CHANGE IN SOCIO-TECHNICAL SYSTEMS

According to Termeer & Metze (2019), changes in socio-technical systems can be achieved through an accumulation of small wins (Termeer & Metze, 2019). Small wins are niche-level innovations that are accomplished by niche actors by dealing with issues in the 'real world' (Weick, 1984). Niche-level innovations have the benefit of low resistance, which gives them the freedom to develop without suppression from the regime level. By approaching the transition towards circular management of EoL PV panels from the niche level, it becomes more manageable to deal with uncertainties that are related to the dominant 'take-make-consume-waste' model (Ghisellini et al., 2016). This is also because many innovations can be developed within niches simultaneously, which creates a series of developments that react to changes within the socio-technical system.

Strategic niche management (SNM) theory provides a framework for the introduction of sustainable innovations by emphasizing the steering of relevant actor groups (Kemp et al., 1998). Central to SNM is the notion that the introduction of innovations is a complex process and has a high likelihood of failure even if new technologies are promising due to mismatches with the existing regime (van Eijck & Romijn, 2008). The SNM approach addresses these issues by advocating the creation of niches to nurture and gradually introduce innovative technologies. This is done via the creation, development, and controlled phase-out of protected spaces for the development and use of promising technologies through experimentation (Raven et al., 2010). The aim here is to (1) learn about the desirability of the technology and (2) enhance further development and the rate of application of the new technology

(Markard et al., 2012). SNM theory suggests that sustainable innovation journeys can be facilitated through establishing “technological niches”. Technological niches are protected spaces that allow for nurturing and experimentation with co-evolution of technology, user practices, and regulatory structures, and facilitate innovation journeys (Schot & Geels, 2008). The main assumption of SNM is that if technological niches are constructed properly, they would function as steppingstones that set about broader societal changes and sustainable development (Schot & Geels, 2008).

According to SNM theory, real-life experimental projects play a key role in establishing new socio-technical arrangements (Schot & Geels, 2008). These often take the shape of pilot projects that involve multiple actors ranging from users and producers to public authorities (Geels, 2004). Often these pilots are ‘protected’ in terms of subsidies by public authorities or strategic investments (Geels, 2004). Important parties in niche networks involve manufacturers, users, researchers, civil society organizations, and governmental organizations but vary according to the specific circumstances (van Eijck & Romijn, 2008). Niches become empowered when expectations become more broadly accepted, when learning processes are aligned into stable configurations or when networks of actors become larger (Kemp et al., 1998). Especially the involvement of more ‘powerful’ actors can stimulate niche-level innovation by providing legitimacy and resources (Geels, 2004). In general, cities provide a promising environment for niche-level developments due to the geographical proximity of stakeholders and their multidisciplinary interaction. Both are considered major drivers of innovation (European Commission, 2019). In this sense, cities can act as incubators and catalysts of socio-economic and environmental change (Wolfram, 2018).

SNM identifies three internal processes required for socio-technical niche success (Kemp et al., 1998). The first process is the articulation of expectations and visions. In SNM, expectations are considered crucial for the development of technological niches as they provide the direction for learning processes. Also, expectations and visions attract attention, which can support the legitimization, protection, and nurturing of the technological niche (Kemp et al., 1998). Secondly, the formation of social networks is considered important to establish a foundation of support for innovative technology. Additionally, social networks also facilitate interactions between relevant stakeholders and provide the necessary resources for expansion, and involve money, people, and expertise (Schot & Geels, 2008). The third internal process concerns establishment of learning processes across multiple dimensions (Kemp et al., 1998). These dimensions overlap with the regime dimensions identified in the MLP (Geels, 2004), and involve technical aspects and design specifications, market and user preferences, cultural and symbolic meaning, infrastructure and maintenance networks, industry and production networks, regulations and government policy, along with societal and environmental effects (Kemp et al., 1998). Adding upon these internal processes, it has been argued that while technological niches have proven to help bring about regime shifts, they cannot do this on their own (Schot & Geels, 2008). Therefore, internal analysis of niche processes is increasingly complemented in academic literature with attention to external processes (Schot & Geels, 2008).

Based on the introduced theories on change in socio-technical systems, the next chapter will explain the conceptual framework that is applied in this research to answer the stated research question.

3.2 CONCEPTUAL FRAMEWORK

Figure 3.4 shows the conceptual framework that is applied in this research to answer the sub-research questions, based on the introduced theories on change in socio-technical systems.

The conceptual framework indicates how barriers sustain the contemporary system for PV panel EoL management, which is characterized by linear and destructive technologies (Cole et al., 2019). Based on findings made in Aminoff and Sundqvist-Andberg (2021) and Zacho et al. (2018), five categories of socio-technical barriers to circularity in WEEE management have been identified: infrastructure and technological, organizational, institutional, supply-chain related, and economic. Barriers have been explained as individual factors that hinder or slow down transformation (Unruh, 2002). Barriers can self-reinforce and interact, which creates lock-in around existing technologies for PV panel EoL management (Geels, 2007; Loorbach et al., 2017). This hinders the implementation of more promising technologies, such as upcycling technologies or innovative reuse strategies. However, the development of promising technologies and practices at the niche level has the benefit of low resistance, which gives them the freedom to freely develop and add up in an accumulation of small wins. An accumulation of small wins can be achieved because many innovations can be developed within niches simultaneously by niche actors through dealing with issues in the ‘real world. This creates a series of developments that react to and can create changes in, the system for PV panel EoL management. Following this line of reasoning, an accumulation of small wins can step-by-step create or drive changes in the contemporary system for PV panel EoL management (Termeer and Metze, 2019).

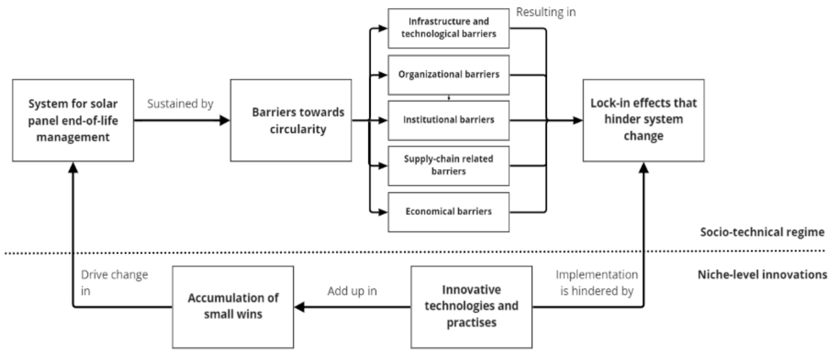

FIGURE 3.4. THE CONCEPTUAL FRAMEWORK FOR THESIS RESEARCH

The next chapter will introduce the research methodology, including the research approach, design, and applied methods.

4. METHODOLOGY

In this chapter, the research approach and the applied methods that were used to answer the research questions are discussed. First, the research approach is introduced and translated into the research design that was used to answer the research questions. Hereafter, the data collection, and the data analysis methods that were applied to answer the research questions are set out and explained.

4.1 RESEARCH APPROACH

This research applies a mixed method approach to identify barriers and promising solution directions to increase the circularity of the EoL management of PV panels located on Amsterdam rooftops. Mixed methods research combines both quantitative and qualitative data collection and analysis to answer the stated research question. Moreover, a mixed methods approach enables the researcher to conceptually and analytically integrate quantitative and qualitative research findings (Tashakkori & Creswell, 2007). The choice for a mixed methods approach was made to provide a broader understanding of the need for better PV panel EoL activities. This was done via quantitative analyses of future PV panel waste streams in Amsterdam and qualitative analysis of barriers and solution directions to improve the PV panel EoL system that manages these waste streams. To be able to answer the main research question, four sub-questions were formulated and divided into three blocks (Table 4.1).

TABLE 4.1. OVERVIEW OF SUB-RESEARCH QUESTIONS PER RESEARCH BLOCK

Block 1: Quantitative analysis of emerging photovoltaic waste streams in Amsterdam
• SRQ1: What is the estimated size of photovoltaic panel waste streams in Amsterdam for the period 2022-2050?
Block 2: Socio-technical analysis of the photovoltaic panel end-of-life management system
• SRQ2: How is the system for end-of-life management of photovoltaic panels currently organized? • SRQ3: What are the barriers to circular photovoltaic panel end-of-life management?
Block 3: Niche-level developments to the increase circularity of end-of-life activities
• SRQ4: What are promising niche-level developments and practices in the Netherlands to upscale circular end-of-life activities for photovoltaic panels?

Different methods have been applied to answer each sub-research question. Figure 4.1 provides an overview hereof and shows how the research blocks and the individual research steps relate to the stated sub-research questions. Figure 4.1 also shows the data gathering methods that were applied in this research. These can be divided into secondary data collection via desk-based research and primary data collection via semi-structured interviews with stakeholders involved in the system for PV panel EoL management. Here, data collection and analysis methods for the systematic literature review have been left out, as these have already been mentioned in chapter 2. The next sections provide a more detailed overview of the applied data collection and data analysis methods.

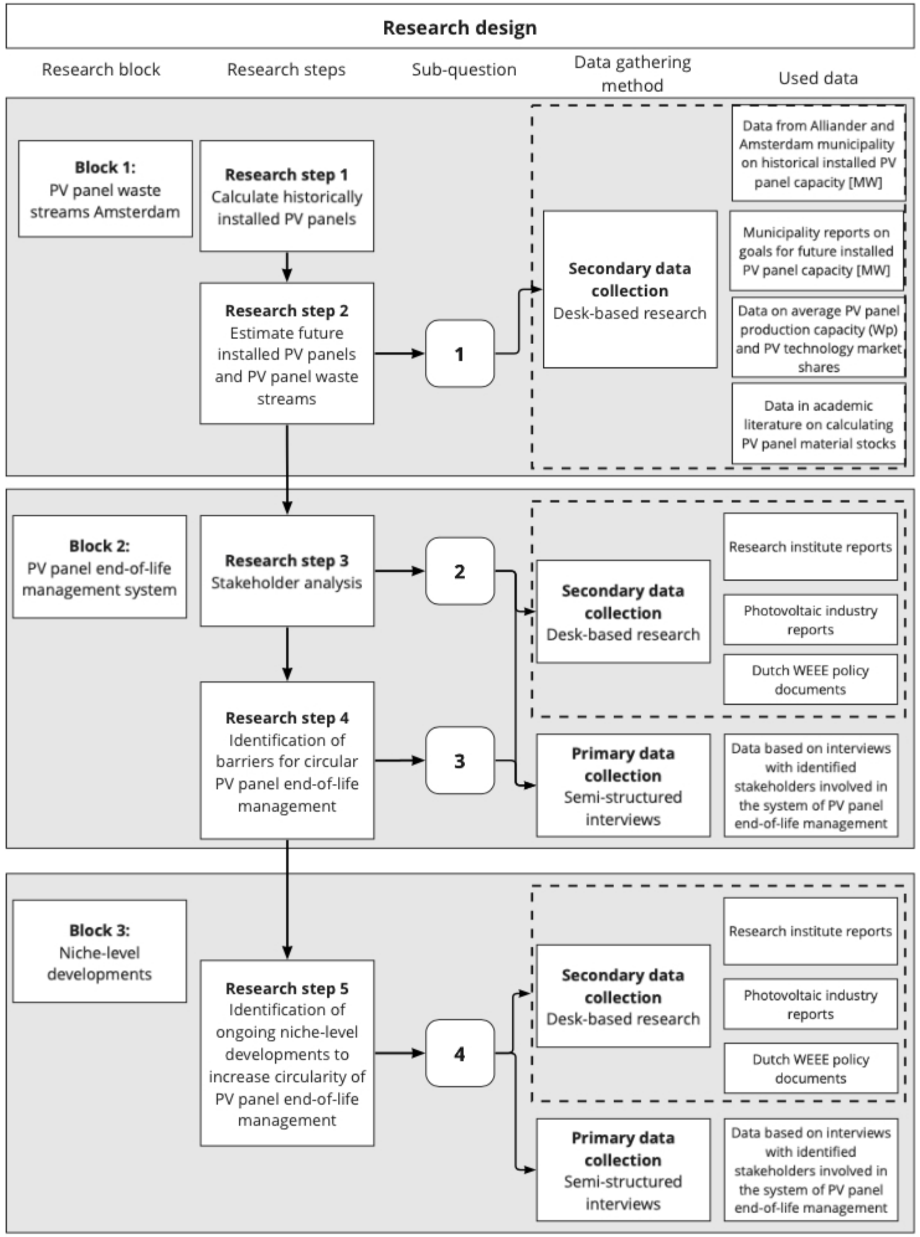

FIGURE 4.1. SCHEMATIC OVERVIEW OF RESEARCH DESIGN

4.2 DATA COLLECTION METHODS

This section sets out the data collection methods applied in this research. As shown in Figure 4.1, both primary and secondary data collection methods were performed. Primary data collection was concerned with semi-structured interviews and secondary data collection was done via document analysis, websites, and newspapers. The choice for multiple data-collection methods was made to increase the credibility of the research findings. Additionally, the findings made in the systematic literature review (chapter 2) serve as background knowledge.

4.2.1 PRIMARY DATA COLLECTION

SEMI-STRUCTURED INTERVIEWS

Interviews were conducted using a semi-structured interview (SSI) approach. SSI is a data-collection method that is used to obtain detailed insights in accord with the expertise and particular perception of the interviewee (Adams, 2015). SSIs can be very useful when exploring complex problems that require expert knowledge. However, a disadvantage of SSIs is that their analysis is time-consuming and labor-intensive (Adams, 2015).

Before the conducted interviews, interviewees received a consent form (Appendix A.1) and the leading interview questions (Appendix A.2*)*. The consent form included information about the processing of information. The leading interview questions provided an overall outline of the topics to be discussed. However, in accord with the SSI approach, the actual questions asked along with the level of detail differed per interview based on the particular expertise of the interviewee (Adams, 2015).

In accord with the data management plan, interviewees have been anonymously categorized in Table 4.2. The categorization was based on the type of company, job, and expertise descriptions. Interviewees were all actors involved in the system for PV panel EoL management. Interviewees represented producer organizations (Stichting OPEN), WEEE collectors (WEEE Nederland), research institutes (TNO), e-waste consultancies (RMC), innovative PV panel manufacturers (Solarge, Sungevity), and public organizations (municipality of Amsterdam & South-Holland province).

TABLE 4.2. OVERVIEW OF INTERVIEWEES

Number	Company	Abbreviation	Description
1	TNO	TNO	Program manager Solar Energy at TNO Energy Transition and coordinating R&D for cells and modules
2	WEEE NL	WNL	Program manager for e-waste management
3	Stichting OPEN	StO	Strategy advisor and counselor for municipalities and government
4	Municipality of Amsterdam	MoA	Program manager solar energy within the Amsterdam sustainability department
5	South-Holland province	SHp	Trailblazer about circular solar energy
6	Solarge	Sol	Strategy and technology manager
7	Exasun	Exa	Product manager
8	New energy and circular raw materials consultancy	RMC	Transition manager circular raw materials

4.2.2 SECONDARY DATA COLLECTION

DOCUMENT ANALYSIS

Document analysis is a systematic procedure for the review and evaluation of documents (Bowen, 2009). In accord with Bowen (2009), all types of documents can support the researcher in uncovering, understanding, and discovering insights relevant to answer a research problem. The main type of documents that were used in this research were reports from the municipality of Amsterdam and reports from, or in collaboration with, research institutes and the PV industry. Table 4.3 provides an overview of these documents; all are in Dutch. Reports that have been identified based on suggestions made in the conducted interviews are marked (*). Additionally, newspaper and website articles have been used when useful to complement, support, or verify research findings.

TABLE 4.3. OVERVIEW OF REPORTS USED TO VALIDATE AND SUPPORT RESEARCH FINDINGS

Year	Report name	Company	Referred to as
2020	Amsterdam Circulair 2020-2050: strategie	Gemeente Amsterdam	Gemeente Amsterdam (2020)
2020	ConceptRES Amsterdam: het bod van deelregio Amsterdam	Gemeente Amsterdam	Prgrammateam Amsterdam Klimaatneutraal (2020)
2021	Een circulaire energie transitie: verkenning naar de metaalvraag van het Nederlandse energiesysteem en kansen voor de industrie	Metabolic, Copper8, Polaris, Quintel	van Exter et al. (2021)
2012*	Kansen en uitdagingen voor circulaire Zon PV: met focus op materiaal en technologie	M2i, provincie Zuid-Holland, Circulaire maakindustrie	Kerp & Jönsthövel (2021)
2021	Kennisnotitie: Zonnepanelen circulair	CE Delft, provincie Zuid-Holland	Beeftink & Bergsma (2021)
2021*	Zonpositief: zonne-energie op weg naar impact	TNO	Sinke et al. (2021)
2021*	Tijd voor duurzame zonne-energie. Zonnestroom: van hernieuwbaar naar duurzaam	TNO	Theelen et al. (2021)
2021	Fair Solar: transitie-agenda voor eerlijke en circulaire zonne-energie	Fair SOLAR netwerk	Fair SOLAR netwerk (2021)
2021*	Roadmap circulaire fotovoltaïsche industrie	Stichting OPEN	Eijsbouts & Jehee (2021)
2021	Impact rapport	ZonNext	ZonNext (2021)
2022	Nationaal solar trendrapport	DNE Research, Solar Solutions International, Techniek Nederland, Holland Solar	DNE Research (2022)
2022	Photovoltaics report	Fraunhofer Institute for Solar Energy Systems	Fraunhofer institute (2022)

*Added based on suggestions made in conducted interviews

4.3 DATA ANALYSIS METHODS

This section sets out the data analysis methods applied in this research. First, the methods applied in the quantitative trend analysis of future PV panel waste streams in Amsterdam are shown. Hereafter, the analysis method for the semi-structured interview data is explained. Then, the methods applied for the stakeholder analysis are elaborated.

4.3.1 QUANTITATIVE ANALYSIS OF PHOTOVOLTAIC PANEL WASTE STREAMS IN AMSTERDAM

A quantitative analysis was performed to estimate the size of PV panel waste streams in Amsterdam for the period 2022-2050. First, historical, and future installed PV panel capacity were estimated. Hereafter, PV panel capacity was transformed into PV panel mass. Based on PV panel mass, the size of PV material waste streams was estimated.

CALCULATION OF HISTORICAL AND FUTURE INSTALLED PHOTOVOLTAIC PANEL CAPACITY

The historical installed capacity of PV panels in Amsterdam over the period 2011-2022 was analyzed using data from Alliander (2022) and the municipality of Amsterdam (Gemeente Amsterdam, 2021). Hereafter, the future installed capacity was calculated using two scenarios. (1) The municipality reaches its goals for installed PV capacity for Amsterdam in 2030 and 2040 (Programmateam Amsterdam Klimaatneutraal, 2020), and (2) the growth trend of PV capacity installed in the past five years in Amsterdam linearly continues to 2030 and 2040.

CONVERSION OF CAPACITY TO PHOTOVOLAIC PANEL MASS (FROM MEGAWATT TO METRIC TONS)

Both the above-mentioned data sources for historical and future installed PV capacity only had data on PV capacity in MW, instead of data on PV panel mass. Therefore, installed PV capacity [MW] was conversed to PV panel mass [tons] by using a weight-to-power ratio [t/MW] calculated in the International Renewable Energy Agency (IRENA) report on end-of-life management of solar photovoltaic panels (Weckend et al., 2016: p 26) (see Appendix B). The weight-to-power ratio was used to translate historical and future installed PV capacity in Amsterdam into PV panel mass via the following formula:

$$PV\ PANEL\ MASS\ [T,\ YEAR_X] = INSTALLED\ PV\ CAPACITY\ [MW,\ YEAR_X] * PV\ PANEL\ WEIGHT\text{-}TO\text{-}POWER\ RATIO\ [T/MW,\ YEAR_X]$$

CONVERSION OF PHOTOVOLTAIC PANEL MASS TO PHOTOVOLTAIC PANEL WASTE STREAMS

Future PV panel waste streams [tons] were calculated by applying an average PV panel lifetime of 20 years (see elaboration for choice of an average 20-year lifetime in Section 5.3). Thus, it was assumed that PV panels that were installed in year x, would reach end-of-life 20 years later. This made it possible to translate installed PV panel mass to future PV panel waste streams.

To estimate the size of specific PV material waste streams in Amsterdam for the period 2011-2050, total PV panel mass was divided into mass streams for glass, aluminum (Al), polymers, silicon (Si), and silver (Ag). Here, a similar approach was applied as done by Kerp & Jönsthövel (2021) in their analysis for expected EoL waste streams in the Netherlands and the South-Holland province for 2030 and 2040:

- Glass constitutes 70% of PV panel mass
- Aluminum constitutes 15% of PV panel mass
- Polymers constitute 10% of PV panel mass
- Silicon constitutes 5% of PV panel mass
- Silver constitutes 0,1% of PV panel mass

Based on this data, PV panel mass streams were calculated using the following formula:

$$PV\ MATERIAL\ MASS\ [T,\ YEAR\ X] = TOTAL\ PV\ PANEL\ MASS\ [T,\ YEAR\ X] * PV\ MATERIAL\ MASS\ [\%]$$

4.3.2 STAKEHOLDER ANALYSIS OF THE SYSTEM FOR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

Stakeholder analysis is seen as the most popular method within actor analysis and is rooted in the strategic management domain (Bryson, 2004). Stakeholder analysis identifies and structures actors and their options to exert control and preferences concerning a specific project (Hermans & Thissen, 2009). In the context of this research, the stakeholder analysis identified the actors involved in PV panel EoL management, along with their interests and influence in this system. Based on Enserink et al. (2010), four steps were conducted:

1. PROBLEM FORMULATION

The analysis aimed to enhance the understanding of the system of PV panel EoL management and to understand if stakeholder interactions contribute to lock-in around linear and unsustainable technologies. This was done by analyzing the relationships between the stakeholders involved in PV panel EoL management, and their interaction dynamics. Specific attention was paid to how these dynamics could create barriers toward circular PV panel EoL management.

2. MAKE AN INVENTORY OF ACTORS INVOLVED

The identification of actors that are involved in the system for PV panel EoL management was an iterative process (Bryson, 2004). Multiple methods supported the initial identification of stakeholders, which complemented each other. An initial inventory of stakeholders was made based on academic and grey literature, policy documents, and research institute and PV industry reports (see Section 4.2.2). Hereafter, the semi-structured interviews with identified key stakeholders were partly used to add on and validate this inventory (see Section 4.2.1).

To ensure that the list of actors did not become extensive and that the network boundaries were clear, three general guidelines were adapted (Enserink et al., 2010):

1. Ensure that the identified actor-network is in line with the chosen level of analysis
2. Ensure that the identified actors cover a balanced set of interests and roles
3. Aim for the stakeholder analysis to encompass between ten and twenty different actors to ensure the validity of analysis results. Less than ten increases the risk that actors are overlooked, while more than twenty can make the analysis insufficiently focused.

3. MAPPING FORMAL RELATIONS

Formal relations between the identified actors were mapped out using a formal chart. A formal chart provides an overview of the hierarchical relations between the actors involved. Hierarchical relations are important since they shape influence and informal interaction processes (Enserink et al., 2010). Furthermore, a formal chart also provides information about resource dependencies between the actors in the network. According to Enserink et al. (2010), formal relations can be described as:

1. Formal positions of actors along with their tasks and responsibilities
2. Specification of formal relations between actors
3. The most important laws, legislations, procedures, and authorities for PV panel EoL management

4. DETERMINING THE INTERESTS, OBJECTIVES, AND PROBLEM PERCEPTIONS OF THE ACTORS

Problem formulations of the identified stakeholders were systematically drafted by assessing stakeholder interests and objectives. This resulted in a table that encompasses stakeholders, their interests and objectives, and problem perceptions (Enserink et al., 2010):

1. Interests refer to the issues that matter most to the actor, these are not linked to a problem situation and are relatively stable. Identification of actor interests supports the estimation to which extent certain objectives and solution directions will be acceptable for the actors involved.
2. Objectives refer to what actors want to achieve given the problem situation. Objectives can be used to translate actor interests into specific and measurable terms and involves what the actors want to achieve and under what conditions? Also, the specific costs and benefits that are associated with a problem or solution direction can be considered here.
3. Perceptions of different actors given a specific problem situation can differ significantly. Rather than mapping out 'which actor is right', it is therefore interesting to map similarities and differences in actor perceptions given end-of-life management.

4.3.3 INTERVIEW DATA ANALYSIS

All interviews were conducted online in Microsoft Teams and were recorded in Microsoft Teams after consent was given by the interviewee. Interview transcripts were made with Microsoft Teams transcription software and were corrected afterward through corrective listening.

Interview transcripts were analyzed with the software ATLAS.ti. First, an initial overview of categories was made. The goal here was to note the occurring topics and the individual aspects within these topics which can be broadly related to the research question. In response to the intensive reading of the interview transcripts, similarities and differences between the interviews were marked and were used to set up the first version of categories for analysis (Schmidt, 2004).

In the second stage of the SSI analysis, the categories were brought together in an analytical guide (Table 4.4.). Thirdly, this analytical guide was used to manually code the transcripts of the conducted interviews. Here, coding refers to linking passages in interview transcripts to a particular category (Schmidt, 2004). This was done via thematic analysis with the software ATLAS.ti.

TABLE 4.4. ANALYTICAL GUIDE: CATEGORIES FOR SEMI-STRUCTURED INTERVIEW ANALYSIS

Contemporary system for end-of-life management of photovoltaic panels
• Stakeholders involved in the system for photovoltaic panel end-of-life management
Barriers to circular end-of-life management of photovoltaic panels
• Infrastructure and technological barriers • Organizational barriers • Institutional barriers • Supply chain-related barriers • Economic barriers
Solution directions to increase photovoltaic panel circularity
• Niche-level developments for photovoltaic panel design and production • Niche-level developments for photovoltaic panel use • Niche-level developments for photovoltaic end-of-life management
Photovoltaic panel reuse as a solution route
Role of pilot projects in stimulating photovoltaic panel circularity

5. RESULTS: END-OF-LIFE PHOTOVOLTAIC PANEL WASTE STREAMS IN AMSTERDAM

In this chapter, the results of the quantitative analysis of EoL PV panel waste streams for Amsterdam are shown for the period 2022-2050. This analysis was performed to enhance insights into the necessity of linking Amsterdam its energy transition to its circular economy ambitions by calculating the size of future PV panel waste streams. The results generated make the need for circular PV technologies more tangible by indicating how substantial sizes of PV materials will be lost without the implementation of better EoL management practices. First, the historical installed PV capacity in Amsterdam is shown. Second, the expected future installed PV capacity is estimated. Based on both historical and future installed PV capacity, an indication is made of the size of the PV material waste streams.

5.1 HISTORICALLY INSTALLED PHOTOVOLTAIC CAPACITY

The historical installed capacity of PV panels for Amsterdam is shown in Figure 5.1. In March 2021, Amsterdam reached the milestone of 500,000 PV panels installed on its rooftops (Seijlhouwer, 2021). As shown in Figure 5.1, this corresponds to a total solar power capacity of roughly 132 MW and an average PV panel production capacity of 264-watt peak (Wp). By the end of 2021, 161 MW of PV capacity was installed in Amsterdam, and increased with 1 MW to a total of 162 MW in March 2022. Taking into account modern PV panels of 330 Wp (AMS Institute, 2021), it can be estimated that between March 2021 and March 2022, an additional 90.000 PV panels have been installed in Amsterdam. Thus, the total amount of PV panels located on Amsterdam rooftops in March 2022 is calculated to be roughly 590,000 PV panels. The next section provides estimations for future installed PV capacity in Amsterdam for the period 2022-2040.

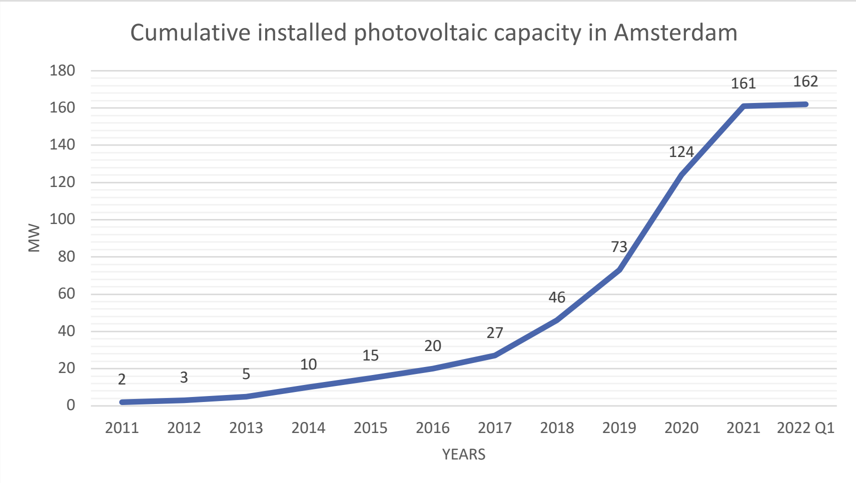

FIGURE 5.1. TOTAL INSTALLED PHOTOVOLTAIC CAPACITY IN AMSTERDAM IN MEGAWATT. DATA SOURCE: ALLIANDER (2022)

5.2 FUTURE INSTALLED PHOTOVOLTAIC CAPACITY

The regional energy strategy of Amsterdam states that the city aims to increase its PV capacity to 250 MW by the end of 2022 (Programmateam Amsterdam Klimaatneutraal, 2020). This corresponds to an average of 1 million PV panels (Seijlhouwer, 2021). Moreover, the municipality aims to increase its solar power capacity to 550 MW by 2030, which corresponds to 1.66 million PV panels with a modern solar panel capacity of 330 Wp. The goal of the municipality is to leave no suitable roof unused by 2040. The PV-advent Calendar project, developed through a collaboration of AMS-institute and TU Delft, analyzed the total PV panel implementation potential for Amsterdam. This tool calculated that to leave no suitable roof unused, a total of 3.25 million PV panels are required in Amsterdam by 2040 (AMS Institute, 2021). This is an increase of factor 6.5 compared to the 590.000 PV panels that have been estimated in the previous section to be located on Amsterdam rooftops already. This results in a total installed capacity of 1074 MW in 2040 if no suitable roof is left unused if the same modern solar panel capacity of 330 Wp is used.

Figure 5.2 shows two scenarios for future installed PV capacity in Amsterdam. The light blue trend (scenario 1) assumes that Amsterdam will reach its targets for 2022 [250 MW], 2030 [550MW], and 2040 [1074 MW]. Here, it is also assumed that PV panel growth is linear between these targets. The light blue trend is compared against the dark blue trend (scenario 2), which takes the growth trend for PV panels installed in Amsterdam over the past five years and assumes that this growth trend will continue linearly towards 2040. This results in a total installed PV capacity of 177 MW by the end of 2022, 411 MW by 2030, and 704 MW by 2040. Moreover, Figure 5.2 also shows that most PV panels are yet to be installed in Amsterdam. Table 5.1 shows the number of installed PV panels that correspond to the installed PV capacity for both scenarios and uses a modern solar panel capacity of 330 Wp.

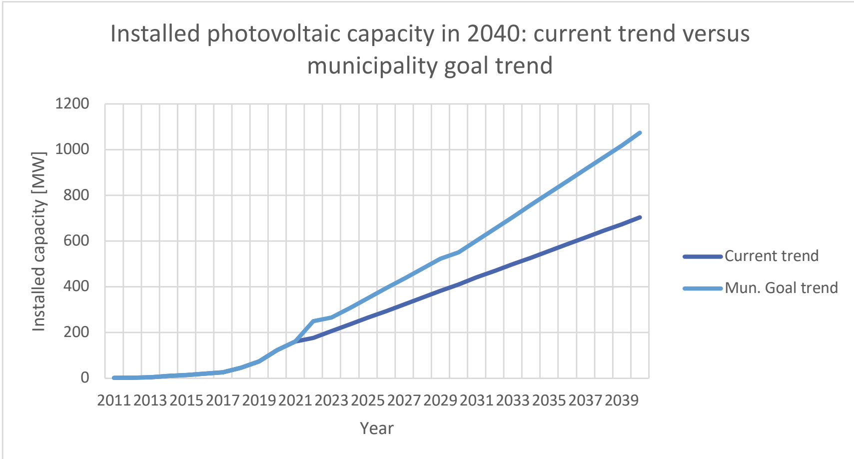

FIGURE 5.2. REQUIRED PHOTOVOLTAIC CAPACITY TO REACH MUNICIPALITY TARGETS FOR 2040 PLOTTED AGAINST THE CURRENT TREND FOR INSTALLED PHOTOVOLTAIC CAPACITY IN AMSTERDAM. DATA SOURCES: A COMBINATION OF ALLIANDER 2022) AND MUNICIPALITY TARGETS (PROGRAMMATEAM AMSTERDAM KLIMAATNEUTRAAL, 2020)

TABLE 5.1. THE ESTIMATED AMOUNT OF INSTALLED PHOTOVOLTAIC PANELS IN AMSTERDAM FOR 2022, 2030 AND 2040

YEAR	NUMBER OF PHOTOVOLTAIC PANELS (CURRENT TREND)	NUMBER OF PHOTOVOLTAIC PANELS (MUNICIPALITY GOAL TREND)
2022 (END)	636,000	1,000,000
2030	1,250,000	1,660,000
2040	2,130,000	3,250,000

A comparison of both scenarios for installed PV capacity by 2040 (Table 5.1) shows that here is a deficit of 1.12 million PV panels [370 MW]. This indicates that based on the calculations made here, substantial increases are required in installed PV capacity in the coming 20 years for Amsterdam to reach its goal to leave no roof unused by 2040. The next section will convert installed PV panel capacity to PV panel mass and calculate the size of future PV material waste streams.

5.3 PHOTOVOLTAIC PANEL WASTE STREAMS

Figure 5.3 provides an overview of estimated future PV panel waste streams in Amsterdam over the period 2031-2050 based on the current trend scenario (1) and municipality goal trend scenario (2). Here, weight-to-power ratios calculated in Weckend et al. (2016) (Appendix B.1) and an average PV panel lifespan of 20 years are applied. The period 2022-2030 is left out because PV panel capacity started to increase from 2011 onwards. Since the average PV panel lifetime is set at 20 years, PV panel streams will start to occur in 2031.

The choice for an average PV panel lifetime of 20 years is made due to the absence of data on the actual lifetime of PV panels registered at the National WEEE register (2020). PV panels are estimated to have an average lifetime of between 15-20 years (ZonNext, 2021). The choice for a 20-year lifetime is supported by the notion that most PV panels in Amsterdam will be located on rooftops and in these types of installments, PV panels tend to remain active as long as possible. Especially if the PV panels are the property of individuals that generate solar power for private use (Theelen et al., 2021).

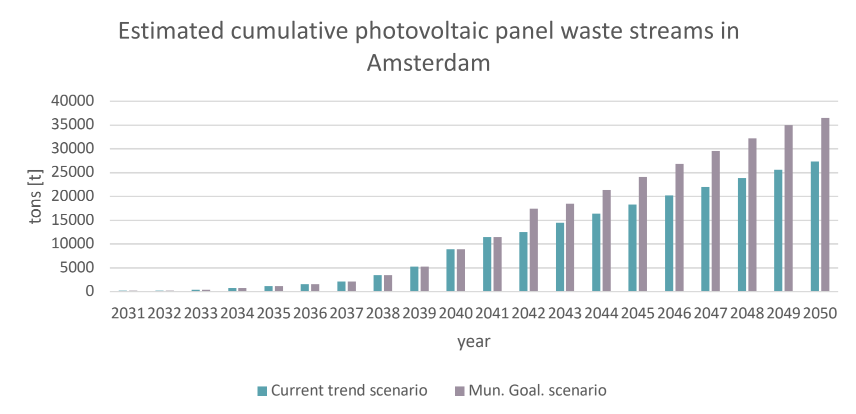

FIGURE 5.3. ESTIMATED CUMULATIVE PHOTOVOLTAIC PANEL WASTE STREAM IN AMSTERDAM.

Based on Figure 5.3, it is estimated that future PV material waste streams in Amsterdam will start to occur in 2031 and will drastically increase in size from 2037 onwards. This is the result of the first generation of PV panels that are installed in Amsterdam and that will start to return based on an average lifetime of 20 years. Table 5.2 provides estimations of the cumulative size of PV material waste streams for 2031, 2040, and 2050. Here, PV panel waste is divided into mass streams for glass, aluminum (Al), polymers, silicon (Si), and silver (Ag). It is assumed that all PV panels that return are c-Si, as these take up >95% of the global market (Fraunhofer Institute, 2022). An additional overview of global PV technology market shares is shown in Appendix C.

TABLE 5.2. OVERVIEW OF CUMULATIVE MASS STREAMS FOR PHOTOVOLTAIC MATERIALS IN AMSTERDAM IN 2031, 2040 AND 2050 [TON/YEAR]

2031	Total	Glass (70%)	Al (15%)	Polymer (10%)	Si (5%)	Ag (0,1%)
Scenario 1	170	119	25,5	17	8,5	0,17
Scenario 2	170	119	25,5	17	8,5	0,17
2040	**Total**	**Glass (70%)**	**Al (15%)**	**Polymer (10%)**	**Si (5%)**	**Ag (0,1%)**
Scenario 1	8,863	6,204	1,329	886	443	9
Scenario 2	8,863	6,204	1,329	886	443	9
2050	**Total**	**Glass (70%)**	**Al (15%)**	**Polymer (10%)**	**Si (5%)**	**Ag (0,1%)**
Scenario 1	27,366	19,156	4,105	2,737	1368	27
Scenario 2	36,477	25,534	5,472	3,648	1824	36

Table 5.2 shows that the largest PV material mass streams consist of glass (70%), followed by aluminum (15%) and polymers (10%). This is understandable given that the aluminum frame and glass together take up >85% of an average c-Si PV panel (Kerp & Jönsthövel, 2021). However, while Ag only takes up roughly 0,1% of the total mass stream volume, it accounts for roughly 65% of the material value (Kerp & Jönsthövel, 2021). Also, when using the current market value for 1 gram of Ag (0.66 euro), the total value of Ag that will be lost in the period 2031-2050 without proper EoL management ranges between 17.8 - 23.8 million euros (27- 36 tons).

5.4 SUB-CONCLUSION

The results in this chapter show that for Amsterdam to reach its goal to leave no suitable roof unused by 2040, substantial increases are required in the installation of additional photovoltaic (PV) capacity in the coming 20 years. It is estimated that if the growth trend for PV panels installed in Amsterdam over the past five years linearly continues towards 2040, there is a deficit of 1.12 million panels to achieve the city its goal of leaving no roof unused. The results also indicate that based on an average lifetime of 20 years, PV panel waste streams in Amsterdam will start to accumulate in 2031 and will substantially increase in size from 2037 onwards. It is estimated that in 2031, the total mass of waste streams is 170 tons, which will increase further to 8,863 tons in 2040 and will range between 27,366 and 36,477 tons by 2050. Glass is calculated to be the largest PV material waste stream and takes up 70% of the mass. Other PV material waste streams are aluminum (15%), polymers (10%), silicon (5%) and silver (0,1%). While silver only presents 0,1% of the volume, it accounts for roughly 65% of the material value.

In the next chapter, a socio-technical analysis of the current system for PV panel end-of-life management is provided and used to identify the barriers to circular PV panel EoL management.

6. RESULTS: SYSTEM FOR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

This chapter provides the results of the socio-technical system analysis for PV panel EoL management. First, the principle of extended user responsibility and its role in shaping the current system for PV panel EoL management is explained. Hereafter, the stakeholder analysis results are shown to analyze how the system for PV panel EoL management is currently organized. Based on stakeholder analysis results, and building further on interview and document analysis insights, barriers to a circular PV panel EoL management system are identified.

6.1 EXTENDED PRODUCER RESPONSIBILITY

The Dutch WEEE directive stipulates that both manufacturers and importers of PV panels in the Netherlands must ensure a system that collects and processes defective products at the end of their lifespan. As result, EoL management of the PV panels located on Amsterdam rooftops is part of a national system for collecting and processing EoL PV panels. This system is organized and financed through the principle of *extended producer responsibility* (EPR). EPR makes manufacturers and importers, together called producers, partly responsible for the EoL management of PV panels. Since the 1st of March 2021, all producers that are subject to EPR are obliged by the Dutch government to register at Stichting OPEN (Beeftink & Bergsma, 2021). Producers need to pay Stichting OPEN a disposal fee and in turn, Stichting OPEN organizes the EoL management for all PV panels located in the Netherlands, and involves collection and processing (Table 6.1: q1: q4). Producers also need to register at the national WEEE register and annually report how many PV panels they have put on the Dutch market in that specific year (Nationaal WEEE Register, 2020). Dutch processers of e-waste also need to register here and report the number of PV panels that they have recycled themselves or exported to other countries. According to the most recent WEEE register report, the amount of PV panels that was returned to Stichting OPEN was approximately 0.2% compared to new installations (Nationaal WEEE Register, 2020). A plausible explanation for why this percentage is so low is because substantial amounts of new PV panels are now being installed compared to the amounts that return. An additional explanation can be given by a lack of EPR enforcement (Beeftink & Bergsma, 2021). This relates to the possible risk that EoL PV panels are not registered and are instead illegally transported to developing countries, where they are either incinerated or landfilled (Deng et al., 2019). The next section will show how the system for PV panel EoL management is currently organized by setting-out the stakeholder analysis results.

TABLE 6.1. QUOTE TABLE: INTERVIEWEES ON ORGANIZATION AND EXECUTION OF EXTENDED PRODUCER RESPONSIBILITY

Theme	Quotes*
Organization and execution of EPR	1. **RMC**: *"Stichting OPEN is responsible for the recycling of all electronics in the Netherlands on behalf of the producers. In principle, Stichting OPEN receives all PV panels, or they ultimately decide which party receives them."* 2. **RMC:** *"In the end, Stichting OPEN is responsible, even if a municipality has already told them 10 times that they must do something, Stichting OPEN must collect the panels. They must ensure that they are processed, that is extended producer responsibility. They can hire companies/organizations to do this for them."* 3. **Sol:** *"At Solarge, we have interpreted the laws and regulations surrounding WEEE and producer responsibility in such a way that only the Stichting OPEN is allowed to do the recycling. It's also fine if they take care of the logistics."* 4. **Exa:**" *As a producer, or as an importer, we must pay a certain amount to what used to be called the PV cycle. It is now called Stichting OPEN. We pay disposal fees and with that fee, they can make the collection of the panels more accessible at recycling centers."*

*Interview brackets refer to interviewee numbers as mentioned in Table 4.5.

6.2 STAKEHOLDERS ANALYSIS RESULTS

The identified stakeholders that participate in the system for PV panel end-of-life management, and their formal relations based on EPR, are shown in the formal chart below (Figure 6.1). An additional overview of stakeholder problem formulations is provided in Appendix D. Creation of the formal chart and the mapping of the formal relations between stakeholders was an iterative process. The overview was verified and complemented by the semi-structured interviews with identified stakeholders, consisting of PV manufacturers, PV waste experts, WEEE organizations, and government entities (see Section 4.2.2). Moreover, the findings in this section are also supported by a document analysis of research institutes and PV industry reports (see Section 4.2.3).

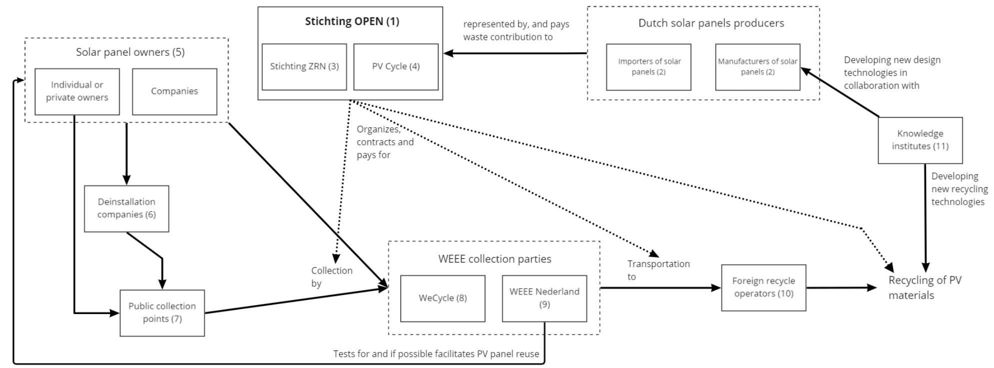

FIGURE 6.1. OVERVIEW OF STAKEHOLDERS ACTIVE IN PV PANEL END-OF-LIFE MANAGEMENT AND THEIR FORMAL RELATIONS BASED ON THE EXTENDED PRODUCER RESPONSIBILITY

Since March 1, 2021, Stichting OPEN (1) has been appointed as the responsible actor for executing EPR on behalf of all producers in the Netherlands. It is the end-responsibility of Stichting OPEN to organize the collection and EoL processing of all electronic waste in the Netherlands (Stichting OPEN, personal communication, May 25, 2022). Therefore Stichting Open contracts collection points, collection companies, and recyclers for end-of-life PV panels (Kerp & Jönsthövel, 2021). All producers that put PV panels on the Dutch market need to pay a disposal fee to Stichting Open to finance the EoL management of PV panels that return in the same year. Here, an exception applies to producers that have successfully set up their own e-waste infrastructure (Solarge, personal communication, April 5, 2022).

All producers (2) must register at Stichting Open and annually report the number of PV panels that they have sold on the Dutch market to the National WEEE register. A part of these producers was already represented or registered at different producer organizations then Stichting OPEN before March 1, 2021. Two of these former producer organizations have become a part of Stichting OPEN: Stichting Zonne-Energie Recycling Nederland (ZRN) and PV Cycle (Table 6.2: q1).

ZRN (3) is part of Holland Solar, which is the Dutch branch organization for PV panels. Before the 1st of March 2021, ZRN existed as an independent producer collective that organized end-of-life management of PV panels on behalf of its affiliated members. ZRN is currently still represented within Stichting OPEN and still represents several manufacturers and importers of PV panels active on the Dutch market. Like ZRN, PV Cycle (4) already existed as an independent producer collective and is currently still represented in Stichting OPEN. PV Cycle also still represents several manufacturers and importers of PV panels that are active in the Dutch market (Eijsbouts & Jehee, 2021).

Handing in PV panels for recycling is free for individuals or private owners (5) of PV panels. They can deinstall PV panels themselves and bring them to a public waste collection point (7). Another option is to hire an uninstallation company (6) to do this for them. The number of collection points and their awareness has increased in recent years: to 71% awareness in 2018 compared to 14% in 2017 (Beeftink & Bergsma, 2021). However, whether it will also be possible to process more than 85% of electronic waste with this mode of recycling is still unsure. For companies (5) that use PV panels on a larger scale, collection must be done directly via an e-waste collection company.

Currently, Stichting Open realizes the collection of PV panels, either from collection points or directly, through two main parties: Wecycle (8) and WEEE Nederland (9) (Table 6.2: q3). It is important to note that Wecycle is part of Stichting OPEN and organizes collection by contracting collection companies such as Renewi or Omrin (Stichting OPEN, personal communication, May 25, 2022; Table 6.2: q2). WEEE Nederland operates as an individual collection company, which is commissioned by Stichting OPEN since the 1st of March, 2021 (WEEE Nederland, personal communication, May 24, 2022). Historically, WEEE Nederland was also an independent producer organization that collected PV panels and WEEE in general. However, in contrast to ZRN and PV Cycle, WEEE Nederland has not become a part of Stichting OPEN (Table 6.2: q4). WEEE Nederland still has an license to collect WEEE until March 1, 2026, and currently still collects roughly 30% of the WEEE market (WEEE Nederland, personal communication, May 24, 2022). Also, WEEE Nederland aims to reuse all the usable PV panels it receives by evaluating PV panel performance in their facility in Apeldoorn. While the second-hand market for PV panels is still considered to be in its infancy, WEEE Nederland states that demand for second-hand PV panels that they offer are increasing due to issues of material scarcity (Table 6.2: q5).

PV panels collected by Wecycle generally go to a recycling facility in Belgium and unusable PV panels collected by WEEE Nederland go to their recycling partners in Germany (Table 6.2: q6 & q7; ZonNext, 2021). In these recycling facilities (10), the vast majority of PV panel materials are pulverized into low-grade building materials or used as fuel in incinerators (Beeftink & Bergsma, 2021). For

example, glass and aluminum are often downcycled as feedstock material in the glass or metal industry or used for asphalt in construction (Circular material consultancy, personal communication, March 5, 2022).

Lastly, research institutes (11) are developing technologies to increase efficiency and sustainability during the PV panel production stage (design) and recycling stage (TNO, personal communication, February 5, 2022).

TABLE 6.2. QUOTE TABLE: INTERVIEWEES ON PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT LOGISTICS AND CURRENT COLLECTION AND PROCESSING ACTIVITIES

Theme	Quotes*
Organization of end-of-life management logistics	1. **RCM:** *"When there was still no full producer responsibility for the Stichting OPEN last March (2021), Holland Solar, the industry association, set up ZRN. Just like WEEE Nederland, ZRN could also facilitate PV panel recycling. ZRN also has a place on the board of Stichting OPEN. ZRN should have been shut down in March last year, but this has not happened. What is happening now is that ZRN advises within the Stichting OPEN. There is also PV Cycle, and nobody understands who PV Cycle is. They say that they are a producer organization, but we still don't know which producers."* 2. **StO:** *"The logistics are all performed by Stichting OPEN, and we just hire contractors for this. These are all direct assignments on behalf of Stichting OPEN. Following this logic, WEEE Nederland is just another contractor for us. We are also the only one that is paying the bill, so we specify where it (PV panels) must go and where it is sorted. and for us it is currently an export line, so we are licensed for this."*
Collection of PV panels	3. **WNL:** *"This is done by two organizations, which are WEEE Nederland and Stichting OPEN or Wecycle. Since March 1, 2021, WEEE Nederland has an agreement for the next 5 years. Whereby we can continue to do the collection and the sorting. This means that we collect about 30% of the market from electronic devices, including PV panels."* 4. **StO**: *"WEEE Nederland likes to pretend that they are the initiators but that is not the case. Previously this was ZRN and PV cycle. Those were the two parties that specifically focused on PV panels. At WEEE Nederland, when it was still separate, and WeCycle, a small amount of PV panels did occasionally arrive at the recycling centers, but the core of the collection happened at ZRN and PV Cycle."*
PV panel processing	5. **WNL:** *"The PV panels in the Netherlands that we collect are partly reused and what cannot be reused is disposed of by the Stichting OPEN for processing through WeCycle" … We see that due to scarcity of materials, the demand for solar panels that we offer for reuse is increasing, also in terms of price."* 6. **StO:** *"At the moment we receive PV panels that have reached end-of-life. These are old and only amount to a few hundred tons a year. This is now collected and transported to Belgium."* 7. **RCM:** *"Stichting OPEN works together with PV Cycle and all those panels go to Belgium across the border to a metal recycler. Here, they remove the aluminum profile and put the glass plate through the shredder, which is then used as raw material in concrete. This is what is happening now in terms of PV panel recycling."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

The next section will take the stakeholder analysis results on step further by categorizing the identified socio-technical barriers that hinder or slow down the implementation of circular solutions in the EoL PV panel management system.

6.3 BARRIERS TO A CIRCULAR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT SYSTEM

This section categorizes the identified barriers that hinder or slow down the implementation of circular solutions in the EoL PV panel management system. These barriers were identified based on the interviews with the identified stakeholders active in the system for PV EoL management. Additionally, document analysis verified and complemented the identification of barriers. Based on the conceptual framework (Section 2.2), the identified barriers are categorized as infrastructure and technological, organizational, institutional, supply chain related, and economical barriers.

6.3.1 INFRASTRUCTURE AND TECHNOLOGICAL BARRIERS

Infrastructure and technological barriers involve existing technological infrastructure, product design, and product characteristics.

Technologies for EoL PV panel upcycling are not considered a constraining factor for the high-value processing of PV panels at EoL (Deng et al., 2019; Table 6.3: q1). This is supported by the high level of research on PV panel recycling technologies, wherein research institutes, such as TNO, play an important role (TNO, personal communication, February 5, 2022; Table 6.3: q2). However, while upcycling technologies have a promising future, they struggle to perform in a system that is linearly designed. Therefore, emerging technologies find it difficult to compete with the low-value recycling activities that currently dominate PV panel EoL management. This is mainly due to issues of scale, as the implementation of PV panel upcycling infrastructure is currently hindered by the high costs associated with developing and especially implementing upcycling technologies and facilities (Stichting OPEN, personal communication, May 25, 2022). Thus, the implementation of upcycling technologies requires large amounts of PV panels to become economically feasible, which is currently not yet the case (TNO, personal communication, February 5, 2022). Additionally, the excessive costs associated with establishing upcycling infrastructure are also caused by the PV panel design during the production stage, which limits panel recyclability.

Contemporary product design is a major constraining factor for increasing PV panel circularity (Table 6.3: q3 & 4). This is because PV panels are currently designed for a long lifetime via the use of ethylene vinyl acetate (EVA) encapsulation (Exasun, personal communication, May 13, 2022). EVA encapsulation is used in the majority of contemporary PV technologies (Deng et al., 2019). The use of EVA hinders the recyclability of PV panels, as the separation of glass, plastic layers, and solar cells cannot be efficiently done without breaking the glass and causing cross-contamination of PV materials (Table 6.3: q5). The limited recyclability is further stimulated by the fact that PV panels are currently not labeled. As a result, no differentiation is made between specific types of PV panels during EoL management (Solarge, personal communication, April 5, 2022).

TABLE 6.3 QUOTE TABLE: INFRASTRUCTURE AND ORGANIZATIONAL BARRIERS

Theme	Quotes*
Recycling infrastructure	1. **StO:** *"The techniques are not that exciting. It is much more in the financing issues surrounding it. Financing and output. Those are the keywords and then you can see which technique you stick behind it"* 2. **TNO:** "*I also know that at TNO there are several projects involving recycling, researching how to disassemble PV panel as well as possible"*
Product design and characteristics	3. **TNO:** *"Current PV panel design is a barrier to circularity if you also include the use of materials. At the moment, the ideal materials are not yet used, and this is also due to the scale: it is not yet commercially attractive to do this"* 4. **Exa:** *"The thing that makes it the most difficult to reproduce a PV panel is the encapsulant used in contemporary PV panel design"* 5. **Sol:** *"Due to the way panels are now made, the separation of the glass and the plastic layers behind it and the cell (encapsulants) cannot be done without breaking the glass."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

6.3.2 ORGANIZATIONAL BARRIERS

Organizational barriers involve the inhibiting factors that result from the contemporary organization of PV panel EoL management (Achillas et al., 2010). The identified organizational barriers are the organization of EPR and the inadequate size of disposal fees.

It was noted that most interviewed stakeholders considered the current organization of EPR as a constraining factor for circularity, while it should be a stimulating factor (Table 6.4: q6). Here, especially the height and use of disposal fees were indicated to be problematic (Table 6.4: q1-q5). The stakeholder analysis showed that Stichting OPEN finances the collection and processing of PV panels by charging the costs of these services in the form of a disposal fee to the producers that put PV panels on the market in that same year (Beeftink & Bergsma, 2021). Via this mechanism, producers that are currently putting panels on the market are not held accountable for the management of these panels when they reach the EoL stage (Beeftink & Bergsma, 2021). As result, the disposal fee for producers that are currently putting PV panels on the Dutch market is roughly 12 euro cents (0,12 euro) per PV panel (Table 6.4: q1-q4). Such a low amount can only cover operations in which PV panels are downcycled through mechanical shredding (Circular material consultancy, personal communication, March 5, 2022). However, disposal fee costs will rise in the future as PV panel return quantities increase in size. This will present future PV panel producers with the bill of costs for recycling the unsustainable PV panels put on the market by their predecessors (Table 6.4: q5).

Interview results also indicated that there are doubts about centralizing EPR execution at Stichting OPEN (Table 6.4: q7-q8). However, Stichting OPEN itself commented that ZRN and PV cycle have consciously lobbied for one Stichting OPEN to effectively organize a good financing mechanism for WEEE management. Since it was considered to be impossible to organize such a mechanism in a competitive market (Stichting OPEN, personal communication, May 25, 2022). Furthermore, Stichting OPEN described the state of the PV panels that are returned to them as *'very old'*, leaving them with no other option than to put these panels through a shredder (Stichting OPEN, personal communication, May 25, 2022).

TABLE 6.4 QUOTE TABLE: ORGANIZATIONAL BARRIERS

Theme	Quotes*
Inadequate disposal fee	1. **SHP:** "The disposal fee *is something like 13 cents per panel? Such an amount is of course too low to organize the sustainable waste collection. I think that this is a constraining factor, that the current amount is so low. For such a low amount there is nothing else you can do than drive to Belgium and throw it in a shredder."* 2. **RCM:** *"Producers shout that they are already paying 12 cents per panel and that they do not want to increase this contribution to 1 or 2 euros because that is too much. If you translate that into what a PV panel costs, it costs say € 150 for convenience, and all those producers are responsible for paying that € 1. They also have no competition differences or disadvantages, so what are we talking about?!"* 3. **RCM: "***The producers do not want to do anything at this moment and with the current disposal fee of 12 cents per panel it is impossible to set something up."* 4. **WNL***: "So how it works now (EPR) is that 13 million panels are being placed on the Dutch market by producer and say that about 60,000 will be collected in that same year. The producers only have to pay a disposal fee for PV panels returning this year, the 60,000 panels. So, the PV panel end-of-life management normally costs 7 euros based on panels placed on the market, but they only pay 12 cents. This is because they are responsible for what is collected this year, not what is collected in the future.* 5. **WNL:** *"You understand that if in the future maybe only 100,000 panels will be put on the market, but the government says producer responsibility and 30 million have to be collected. That 30 million, if you have to convert it over those 100,000 panels, of course, that is not possible. Then producers will choose to not put panels on the market that year because they cannot afford it."*
Organization of EPR	6. **WNL:** *"Producer responsibility is currently still a constraining factor, while it should be a stimulating factor"."* 7. **MoA:** *"I would find it a shame if producer responsibility were executed by one organization. While this could be beneficial, it can also be perceived as ill-management of a major issue. I am not deeply involved enough to see if this is a benefit or not."* 8. **WNL:** *"Producer responsibility, as it is organized now, is like a butcher that performs a quality test on its products".*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

6.3.3 INSTITUTIONAL BARRIERS

Institutional barriers encompass the legal framework and the absence of policy interventions (Unruh, 2002). Policy forms an integral part of a socio-technical system as it forms the course of action proposed by organizations and individuals, shaping the framework wherein a regime operates (Geels, 2004). Here, recycling based on weight and subsidy grants were identified as barriers to circular EoL management of PV panels.

In accord with the European WEEE policy, minimum PV panel recycling percentages are currently based on weight (Beeftink & Bergsma, 2021). Recycling based on weight scores well as it makes it seem as if high degrees of PV panel is recycled in the Netherlands: >85% based on weight. However, this 85% is already obtained by only recycling the aluminum frame and crushing the glass sheet, while all critical materials are lost in the process (Table 6.5: q1). Recycling based on weight does not provide an incentive for PV panel upcycling since PV panel producers and recyclers are currently following WEEE standards for minimum recycling percentages (Table 6.5: q2-q3). Therefore, it is important to critically assess how WEEE targets should be met in the Netherlands.

Moreover, subsidy grants for sustainable energy production in the Netherlands are found to only focus on generation capacity instead of indicators relating to sustainability (Table 6.5: q4-q5). The current design of such subsidy schemes is a good example of the tensions between reaching energy-transition and CE targets, as they form a stimulating factor for the energy transition in terms of PV panel installation but do not consider PV panel management at EoL (Beeftink & Bergsma, 2021). Furthermore,

the current design of similar subsidies also stimulates that PV panels are replaced based on business cases that consider economic rather than a technical lifetime (Circular material consultancy, personal communication, March 5, 2022).

TABLE 6.5. QUOTE TABLE: INSTITUTIONAL BARRIERS

Theme	Quotes*
Recycling based on weight	1. **TNO:** *"PV modules currently fall under the Producer Responsibility Act. This means that 85% of the mass must be recycled. Those are the only the glass plate and the aluminum frame, then you are almost at 85%. But it is precisely the materials with a high value that matter, that are scarce or cost a lot of energy, and nothing or hardly anything is done with them."* 2. **TNO:** "*Weight-based recycling must change anyway; I think it is important to look at value. This also applies to current legislation, which should encourage modules to be recyclable, so that you look beyond what is currently happening."* 3. **WNL:** "Producers s*ay that they want everything, but are not acting upon it, that is the limiting factor at the moment. Stichting OPEN says that between 85-90% is recycled. Yes, by weight but not by quality. That is why we have always said: we want to move towards recycling based on quality"*
Subsidy grants	4. **TNO:** *"This also applies to the current subsidy scheme, SDE, SDE++, etc., these still focus too much on PV panel costs and not on value."* 5. **WNL:** *"That means that the government said: "Let us give a subsidy for PV panels, then we will sell a lot of them, and everyone will get them on their roofs. Then we are doing well with the energy transition." The government assumes that the cleaning up of these panels is not their concern because that is up to the producers."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

6.3.4 SUPPLY CHAIN-RELATED BARRIERS

Supply chain-related barriers focus on the relationships between actors throughout the PV supply chain (Aminoff and Sundqvist-Andberg 2021).

The existing PV supply chain in the Netherlands is perceived as well established. However, the implementation and adoption of more innovative closed-loop solutions are hindered by a lack of collaboration throughout this supply chain. First, there is a lack of collaboration between PV panel manufacturers and PV panel recyclers. This is understandable given that most PV panels are imported from China, which makes it difficult to establish strong collaboration between Chinese manufacturers and European recycling operators (Table 6.6: q1). Second, there was found to be competition, instead of collaboration, between WEEE collection parties. As PV panel collection operators must compete for contracts that are tendered by Stichting OPEN (Table 6.6.: q2).

TABLE 6.6. QUOTE TABLE: SUPPLY CHAIN-RELATED BARRIERS

Theme	Quotes*
Lack of collaboration throughout the photovoltaic supply chain	1. **TNO:** *"Large scale placement of solar panels is quite possible, however not with the one-size-fits-all models that are currently produced in enormous quantities in China."*
Competition between WEEE collection parties	2. **StO:** *"We must first ensure that there is a financial basis, and we are working on that. Then we will tender pilots (for PV panel upcycling) because all those parties (WEEE operators) have all submitted requests for pilots. We only have a few hundred thousand euros, so we can only give the tender to one party."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

6.3.5 ECONOMICAL BARRIERS

The last category of barriers is related to economic factors and incentives for the adoption and diffusion of alternative recycling infrastructure. Here, cost efficiency and the availability of EoL PV panels were found to be the primary limiting factors.

Product price, instead of product sustainability is considered a key factor for PV panel procurement along with product lifetime and production capacity. This affects circular PV EoL management due to issues of lifetime versus recyclability, as mentioned in Section 5.3.1. This is the case for >95% of the PV panels installed (Fraunhofer Institute, 2022). As these are all made using c-Si technologies and most c-Si panels are produced in China, where PV panel prices are currently the lowest (Table 6.7: q1). Likely, PV manufacturers will only increase product circularity if this goes hand-in-hand with a more favorable business case or with changes in legislation for PV panel production or use (Beeftink & Bergsma, 2021; Table 6.7: q2).

Also, quantities of returning PV panels are currently low: 0,2% compared to the amount of PV panels placed (Nationaal WEEE Register, 2020; Table 6.7: q3). This furthermore affects circular WEEE management as adaptation and diffusion of innovative recycling technologies require high quantities of PV panels to become economically feasible (Table 6.7: q4). The low amount of EoL PV panels that are currently returning is also partly caused by reuse activities via second-hand markets or export (Table 6.7: q5). Additionally, the use of EVA encapsulant in contemporary PV technologies has already been explained to result in economic barriers as the use of EVA limits PV recyclability and results in higher costs for upcycling.

TABLE 6.7. QUOTE TABLE: ECONOMICAL BARRIERS

Theme	Quotes*
Cost efficiency	1. **RCM:** *"The problem with designing sustainable panels is that they are still too expensive compared to Chinese panels, which is a market situation."* 2. **SHP:** *"You can't change the market by doing the same thing over and over, so you'll have to do something else that will probably be more expensive initially. That is necessary, I think, for change. A positive business case should not be the incentive."*
Availability of end-of-life photovoltaic panels	3. **StO:** *"The number of PV panels returning is currently so low that you would only need one recycling facility for the whole of Europe."* 4. **StO:** *"Financing and output, those are key. A lot of technologies are already available, but their financing poses a similar problem."* 5. **WNL:** *"We see increases in PV panel reuse. Also, via foreign outlet channels, where the sun is always shining."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

6.4 SUB-CONCLUSION

This chapter has shown that extended producer responsibility (EPR) plays a leading role in shaping the system for EoL PV panel management. An overview was provided of stakeholders active in the system for PV panel EoL management via the creation of a formal chart. Here, Stichting OPEN was identified as a key stakeholder because of its role as the responsible actor for EPR execution on behalf of all PV producers in the Netherlands. It is the end-responsibility of Stichting OPEN to organize the collection and EoL processing of all electronic waste in the Netherland, which is done via the commissioning of contractors. PV panels were found to be collected on a national scale by a variety of WEEE operators and transported to recycling facilities in Belgium and Germany, where the panels are pulverized into low-grade building materials or used as fuel in incinerators. PV panel reuse is not found to be widely incorporated in the contemporary system for PV panel EoL management in the Netherlands. The only party identified to be already working on PV reuse is WEEE Nederland, a Dutch WEEE operator that collects roughly 30% of WEEE in the Netherland. While the Dutch market for second-hand PV panels is stated to be still in its infancy, WEEE Nederland found that demand for their second-hand PV panels is increasing due to issues that relate to material scarcity. Moreover, multiple barriers that hinder or slow-down implementation of circular solutions in the EoL PV panel management system were identified and categorized. The identified barriers have been categorized as infrastructure and technological, organizational, institutional, supply chain related, and economical barriers. An overview of these barriers is shown in Table 6.8.

TABLE 6.8. SUMMARY OF IDENTIFIED BARRIERS FOR A CIRCULAR SYSTEM FOR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

Category	Barrier
Infrastructure and technological	1. Contemporary product design focuses on lifetime instead of recyclability 2. The absence of photovoltaic panel labels results in a one-size-fits-all recycling process
Organizational	3. The size of disposal fees is inadequate to finance high-quality recycling activities 4. Lack of future accountability in finance mechanism for disposal fees
Institutional	5. Minimum photovoltaic panel recycling percentages are based on weight instead of value 6. Dutch photovoltaic panel subsidy grants (SDE++) focus on generation capacity instead of indicators relating to sustainability and circularity 7. Photovoltaic panel subsidies stimulate that replacement based on economic lifetime
Supply chain related	8. Competition between WEEE operators 9. Lack of trust between WEEE management actors
Economical	10. Procurement of photovoltaic panels is price-driven 11. Upcycling infrastructure is not financially feasible due to limited photovoltaic panel return quantities 12. Use of ethylene vinyl acetate encapsulant hinders cost-effective upcycling

The next chapter will provide the results for the identified niche-level innovations and practices throughout the PV supply chain in the Netherlands that act as solution direction to overcome the identified barriers.

7. SOLUTION DIRECTIONS TO INCREASE THE CIRCULARITY OF PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

This chapter sets-out the identified niche-level innovations and practices to increase the circularity of PV panel end-of-life management within the context of the Netherlands. These developments serve as solution directions to overcome the identified barriers in the previous chapter (Table 6.8). Like the identification of barriers, these developments are identified based on expert interviews with PV manufacturers, PV waste experts, WEEE organizations, and government entities (see Section 4.2.2). Furthermore, the findings are verified and complemented by a document analysis of research institutes and PV industry reports (see Section 4.2.3). First, the innovations and practices to increase PV circularity are discussed as sub-niches along the PV supply chain in the Netherlands. Hereafter, the identified niche-level innovations, and practices are presented in accord to the phases of the PV supply chain: design and production, user-phase, and end-of-life.

7.1 NICHE-LEVEL DEVELOPMENTS ALONG THE DUTCH PHOTOVOLTAIC SUPPLY CHAIN

The results in the previous chapter indicated that circular PV panel EoL management requires changes throughout the entire PV supply chain. Ideally, this entails that the design and production of PV panels also consider the recyclability of the product at EoL. Thus, an increase in PV panel circularity at EoL appears to be inextricably linked to the earlier phases of the PV supply chain. This makes it relevant to discuss experiments in multiple stages of the PV supply chain as sub-niches along this chain. Niches have been conceptualized as technological incubators in which innovative practices and breakthroughs are nurtured (Geels, 2004). In the context of this research, 'experiments' are understood as activities undertaken to enhance PV circularity. These developments involve a broad range of actors as identified in the stakeholder analysis and ranges from PV panel manufacturers, users, and producers to public authorities. A schematic overview of the role of niche-level developments to change the socio-technical system for PV EoL management is shown in figure 7.1.

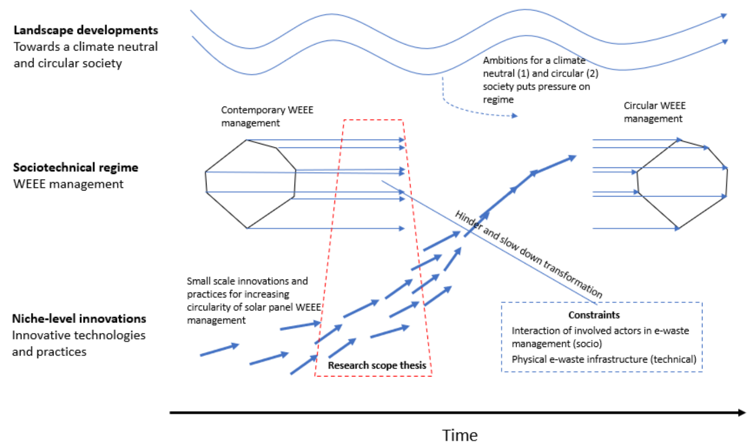

FIGURE 7.1. MULTI-LEVEL NICHE PERSPECTIVE ON THE ROLE OF BARRIERS AND NICHE-LEVEL DEVELOPMENTS IN ESTABLISHING A CIRCULAR SYSTEM FOR END-OF-LIFE PV PANEL MANAGEMENT. FIGURE BASED ON MLP OF GEELS (2004)

The next sections will set out the identified activities in the Netherlands to increase the circularity of PV panel EoL management. These sections are categorized in accord to the phases of the PV value chain: design and production (1), user-phase (2), and end-of-life (3).

7.2 PHOTOVOLTAIC PANEL DESIGN AND PRODUCTION

Two sub-categories are distinguished for developments in the design and production of PV panels. The first sub-category is concerned with changing PV panel design to allow for better separation of PV materials at EoL. This development is referred to as 'design for recycling'. The second sub-category is the use of material passports to increase the traceability of PV materials and optimize recycling processes.

7.2.1 DESIGN FOR RECYCLING

Design for recycling (DfR) refers to the simple and environmentally friendly dissemblance of a PV panel (Theelen et al., 2021). This is both a scientific and technical challenge that aims for better recovery of PV components, thereby also enabling PV components to be repaired and reused. This links to the principle of 'modular design', which allows for PV panels to be subdivided into smaller parts that can be independently replaced or exchanged with other PV panels (Exasun, personal communication, May 13, 2022). DfR also focuses on decreasing the use of scarce and harmful materials, while maintaining or improving panel functionality. Practice shows that the direct transition to industrial fabrication of a complete DfR-based PV panel is currently a step too far (TNO, personal communication, February 5, 2022). However, if components are gradually being introduced into PV production. The most promising technological developments for DfR in the Netherlands that are identified in this research are the replacement of EVA encapsulant and the replacement of toxic materials.

<u>REPLACE EVA ENCAPSULANT</u>

EVA encapsulation material is used in c-Si PV technologies, which currently constitute over 95% of the global PV market (Fraunhofer Institute, 2022; Sinke et al., 2021). Replacement of EVA encapsulant is a promising technological development given that EVA encapsulation material has been identified as a bottleneck for reparation, modular reuse, and cost-effective upcycling of PV panel cells and glass (TNO, personal communication, February 5, 2022). One of the most promising technological developments in the field of DfR focuses on replacement of EVA encapsulation material in c-Si PV panels with a reversible encapsulant or 'release foil' (Kerp & Jönsthövel, 2021; Table 7.1: q1). A release foil is currently being developed by a consortium of Dutch companies in the 'PARSEC' project, and includes the companies TNO, DSM, Mat-Tech, and Exasun (Kerp & Jönsthövel, 2021). This research was also funded by a 300,000 euro governmental subsidy (Topsector Energie, n.d.). The PARSEC project runs from 2020-2022 and aims to optimize its release foil in terms of production process and materials, upscaling, and product reuse (Kerp & Jönsthövel, 2021). Furthermore, Solarge is also collaborating on a research project called RAPID with SABIC. Together, these companies have developed a lightweight plastic PV panel. This panel is completely circular, as the material layers can be separated and individually recycled (Solarge, personal communication, April 5, 2022).

REPLACEMENT OF TOXIC MATERIALS

Currently, Tedlar is the cheap and standard application used in c-Si PV panel backsheets. Tedlar is a PFAS and is used in backsheets to ensure stiffness and water resistance (Beeftink & Bergsma, 2021). Tedlar is difficult to recycle, as it is identified as a very worrisome substance that endangers human health. Therefore, there is a risk that Tedlar recycling could lead to harmful fluorine compounds to end up in the environment (TNO, personal communication, February 5, 2022). Three projects in the Netherlands are identified to be currently working on PFAS-free backsheets (Kerp & Jönsthövel, 2021). In the PARSEC project, Tedlar is replaced by a glass plate (Exasun, personal communication, May 13, 2022). In the RAPID project, the lightweight PV panels use alternative PFAS-free backsheet polymers to replace Tedlar (Solarge, personal communication, April 5, 2022). Thirdly, there is also Energyra which is currently working on a PFAS-free PV panel design (TNO, personal communication, February 5, 2022). Like Solarge and Exasun, Energyra is also a Dutch PV manufacturer.

7.2.2 MATERIAL PASSPORTS

The use of material passports is a promising solution direction to label PV panels based on their material composition and environmental impact, which allows for optimization of recycling processes (Table 7.1: q3). Here, a database with material passports is suggested as a promising tool (Theelen et al., 2021). A material passport can store valuable data on PV panel composition in a publicly accessible database. This makes it possible to optimize recycling processes by sorting PV panels based on their data. Additionally, recovery percentages can be increased by sorting PV panels according to their type and composition (Theelen et al., 2021). At the time of writing, no projects working on PV panel material passports have been identified in the Netherlands. However, the FAIR SOLAR network has suggested experimentation with a national commodity bank for raw materials (FAIR SOLAR netwerk, 2021). This is an organization that pushes for a circular Dutch PV sector by bringing together all actors that want to take steps towards more circular and fair solar energy. These actors include governmental organizations, research institutes, experts, and other enthusiasts. A national commodity bank for raw materials links to the idea of material passports, as this supports a smart track-and-trace system that monitors PV panel material streams within the Netherlands.

TABLE 7.1. QUOTE TABLE: EXPERIMENTS IN PV PANEL DESIGN AND PRODUCTION

Theme	Quotes*
Replace EVA encapsulant for release foil	1. **Exa:** "I think that *design for recycling and reversible encapsulants are the biggest developments in product design. Then you could completely separate a PV panel, which would be fantastic"*
Replacing toxic materials	2. **TNO**: *"This is also not useful for recycling, so it is better to avoid putting harmful materials in it than having to recover them later"*
Material passports	3. **Exa:** *"I don't think you can avoid starting mapping it out properly. That it somehow becomes easier and better to keep track of what materials are used, what the energy flows of many producers are, and that there will be some kind of database with good data."*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

7.3 PHOTOVOLTAIC PANEL USE

Three categories of developments are identified concerning PV panel use in the Netherlands. The first development is extending PV panel life via reuse activities. The second-development entails setting-up sustainable criteria for PV panel procurement via buyer groups. The third development is concerned with increasing the height of disposal fees.

7.3.1 EXTENDING PHOTOVOLTAIC PANEL LIFE VIA REUSE ACTIVITIES

When considering PV panel reuse, a differentiation must be made between panels located in large scale installations, using the example of professional solar parks, and individual use (Stichting OPEN, personal communication, May 25, 2022).

Professional solar parks have substantial quantities of PV panels and thus in their case, financial returns are more relevant. This is explained by the economic lifetime of PV panels, where costs of investments are currently earned back in roughly 6 years (Circular material consultancy, personal communication, March 5, 2022). This is also due to the considerable increase in PV panel production rates and affordability (Beeftink & Bergsma, 2021). Early replacement of PV panels is further stimulated by SDE++ and similar subsidies (TNO, personal communication, February 5, 2022). Stichting OPEN estimated that PV panel replacement in professional solar parks becomes economically feasible after a period between 10-15 years. PV panels that are replaced within this period still have economical value. Therefore, it would be a logical step for project developers to re-sell these PV panels on the Dutch second-hand market or export them to countries with more sun. Individual users are less likely to replace PV panels before the end of their lifespan due to the lower amount of PV panels that are used. Early replacement here becomes less attractive because circa 40% of the costs of PV panel installation account for the panel itself and the remaining 60% results from fees, such as installation services. Therefore, individual owners likely hold on longer to their PV panels, which decreases reuse potential (Stichting OPEN, personal communication, May 25, 2022).

Due to the rapid increases in production rates and affordability of new PV panels, the reuse of older modules in the Netherlands is considered to be primarily interesting for temporary locations, locations where space is not a problem (large roofs), or locations that have limited grid integration (Beeftink & Bergsma, 2021). An exception applies to PV panels that are still in a particularly good state, for example, due to premature removal as in the example given for professional solar parks. The second-hand market for private individuals and project developers appears to be still in its infancy (Beeftink & Bergsma, 2021). However, interview data did point out that due to the scarcity of materials, demand for second-hand PV panels is increasing (Table 7.2: q1). The only project within the Netherlands that is identified to be currently working on PV panel reuse is ZonNext. An online platform that links second-hand PV panel supply to demand. ZonNext is set up in a partnership with WEEE Nederland. WEEE Nederland collects, tests, and certifies second-hand PV panels for them to be reused (ZonNext, 2021). Moreover, ZonNext is currently involved in the setting-up of a pilot project on local PV panel reuse in Amsterdam Zuid-Oost in cooperation with the municipality of Amsterdam, AMS-institute, TU-Delft, Sungevity, WEEE Nederland, ROC, and local organizations. Here, it is explored under what conditions second-hand PV panels are an interesting product for households with a limited budget.

Another option is to reuse PV panels for a different function, thereby also increasing the life length of individual products. The Dutch initiative Boldz is currently experimenting with second-life opportunities for PV panels such as energy-generating tables, blackboards, and off-grid systems for e-bikes. These kinds of solutions require out-of-the-box thinking that could provide additional functions for second-hand PV panels that would be recycled otherwise (FAIR SOLAR netwerk, 2021).

7.3.2 PROCUREMENT CRITERIA

Sustainable procurement criteria provide an promising way to promote PV panel end-of-life management in the Netherlands, according to the governmental organizations interviewed (Municipality of Amsterdam, personal communication, May 24, 2022). This is because procurement criteria can include indicators besides PV panel price such as product circularity, environmental impacts of materials, presence of toxic substances, lifetime, and the working conditions wherein PV panels are produced (Table 7.2: q2). Currently, a national buyer group is being set up by the Dutch implementation program for the circular manufacturing industry (Uitvoeringsprogramma Circulaire Maakindustrie). Here, also TKI Urban Energy and PIANOo, which is the expertise centrum for procurement by the Dutch Ministry of Economic Affairs and Climate, are involved (Municipality of Amsterdam, personal communication, May 24, 2022). Multiple governmental bodies, including the municipality of Amsterdam, are already connected to this buyer group along with transportation and energy companies such as ProRail, Eneco, and HVC. The setting-up of this national buyer group is an interesting development because it can serve as a platform for learning about, and facilitation of, collective procurement of PV panels for interested parties. These parties can range from governmental to commercial organizations. Also, procurement criteria can be applied in tenders, for example for the rooftops of municipality buildings. Furthermore, the European Commission adopted a proposal in 2021 for a carbon border adjustment mechanism (CBAM) that will create carbon pricing on imported products (European Commission, n.d.). CBAM is expected to become operational in 2026 and supports the creation of sustainable procurement criteria by including environmental costs into PV panel pricing (Solarge, personal communication, April 5, 2022).

7.3.3. INCREASE DISPOSAL FEE

It is crucial to include future accountability in EPR to finance high-quality recycling activities and to support upcycling infrastructure. This can be done by revision of the finance mechanism that determines the size of the disposal fee that PV producers must pay (Table 7.2: q3). This mechanism must hold producers that put PV panels on the market today accountable for the future collection and processing of these panels when they reach EoL (WEEE Nederland, personal communication, May 24, 2022). It is stated that revising the finance mechanism to include future accountability would increase the height of disposal fees from 0,12 eurocents to around 7 euros per panel (WEEE Nederland, personal communication, May 24, 2022). This increases the funds for a high-value recycling infrastructure with a factor 60 with only a slight increase in PV panel price. This makes it substantially more manageable to establish a circular system for PV panel EoL management. On December 9th, 2021, a roadmap toward a circular PV industry was published by Stichting OPEN: the executive Dutch organization for producer responsibility. This roadmap states, among others, that the PV industry will create a stable, fraud-proof financing mechanism for PV panel EoL management with the help of government support. Which suggests that processes are in motion to guarantee that removal funds will become available for the collection and high-quality processing of PV panels at end-of-life (Eijsbouts & Jehee, 2021).

TABLE 7.2. QUOTE TABLE: EXPERIMENTS IN PV PANEL USE

Theme	Quotes*
Photovoltaic panel reuse activities	1. **WNL:** *"It was initially said by producers that the reuse of PV panels is not a market. What we see now is that due to the scarcity of raw materials, prices of PV panels that we offer for reuse are rising and demand is increasing. So, we see that there is indeed a market for it."*
Procurement criteria	2. **SHp:** *"I think that procurement criteria are very important. So, setting criteria for sustainability in tenders or something like that. This is mainly about three things: the CO_2 impact of PV panels, toxic materials, and working conditions. So how are people paid and under what conditions are they working? Oh, also fourth criteria could be about lifetime."*
Increase disposal fee	3. **StO:** *"Our entire lobby is aimed at increasing the disposal fee, and the government is also involved in this. … We just need the research results with TNO to provide sufficient arguments to raise the disposal fee. That's the whole crux of this matter"*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

7.4 PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT

A contested development to support value-based recycling in the Netherlands is the setting-up of a Dutch pilot upcycling facility.

7.4.1 DUTCH UPCYCLING FACILITIES

WEEE Nederland has submitted a plan in cooperation with TNO to establish a pilot facility for PV panel upcycling in the Netherlands (WEEE Nederland, personal communication, May 24, 2022). However, at the time of writing, this plan has not yet been approved by Stichting OPEN, since multiple parties have indicated to be interested in setting-up similar projects (Stichting OPEN, personal communication, May 25, 2022). Therefore, Stichting OPEN is currently setting up a tender document that includes minimum material requirements that the material output of suggested pilot projects must meet. However, funding pilots for high-value PV panel recycling in the Netherlands is contested, given that most pilots on PV recycling are stated to have already been performed in the European context (Table 7.3: q1). For example, a European subsidy has been granted to the French company ROSI Solar to pilot innovative solutions for recycling and revalorization of raw materials in the PV industry. Similar subsidies have also been granted to Veolia in France and Reiling Recycling GmbH in Germany (Stichting OPEN, personal communication, May 25, 2022). This also raised questions by interviewed stakeholders concerning the need for pilots for PV recycling in the Netherlands (Table 7.3: q1-q2). Contemporary PV panel design has been explained to use EVA encapsulant, which hinders product recyclability at EoL. Therefore, technological developments of recycling technologies focused on the clean separation of the glass sheet and solar cells. Hence, there is already a wide variation of recycling techniques available, which includes mechanical, chemical, magnetic, and metallurgic upcycling techniques (Kerp & Jönsthövel, 2021).

TABLE 7.3. QUOTE TABLE: EXPERIMENTS ON PV PANEL END-OF-LIFE MANAGEMENT

Theme	Quotes*
Dutch upcycling facilities	1. **Sol:** *"Looking at the lessons learned I am pretty critical about all the enthusiasm here in the Netherlands. Because what is the use of reinventing the wheel."* 2. **StO:** *"As a matter of fact, all pilots have already been done within the European context. … We can do the same pilot project again in the Netherlands but actually, everything has already been done once"*

*Interview brackets refer to interviewee numbers and abbreviations as mentioned in Table 4.5.

7.5 SUB-CONCLUSION

This chapter identified multiple innovations and practices that can function as solution directions to the barriers found for circular PV panel end-of-life (EoL) management in the Netherlands. It was suggested that an increase in PV circularity at EoL is inextricably linked to the earlier phases of the PV supply chain. Therefore, identified innovations and practices have been framed as sub-niche experiments along the PV supply chain in the Netherlands. In the context of this research, 'experiments' are understood as activities undertaken to enhance PV circularity. These developments involve a broad range of actors as identified in the stakeholder analysis, which ranges from PV panel manufacturers, users, and producers to public authorities. To conclude, this chapter has shown that innovation and practices to increase PV circularity at EoL are happening simultaneously and throughout the PV supply chain. An overview of how these developments can function as solution directions is shown in Figure 7.2. The developments are categorized according to the R-ladder of circular strategies as introduced in Potting et al. (2017). Furthermore, the results show that especially technological developments that focus on PV panel design and the development of upcycling technologies often take the shape of experimental projects. These types of projects are generally protected in terms of government subsidies or strategic investments. Here, PARSEC forms a good example: a government-funded project that involves multiple actors, including PV industry producers and public authorities.

The next chapter will discuss the research findings compared to existing literature, reflect on the applicability of socio-technical system theory, reflect on the research limitations, and set-out the research implications for knowledge users.

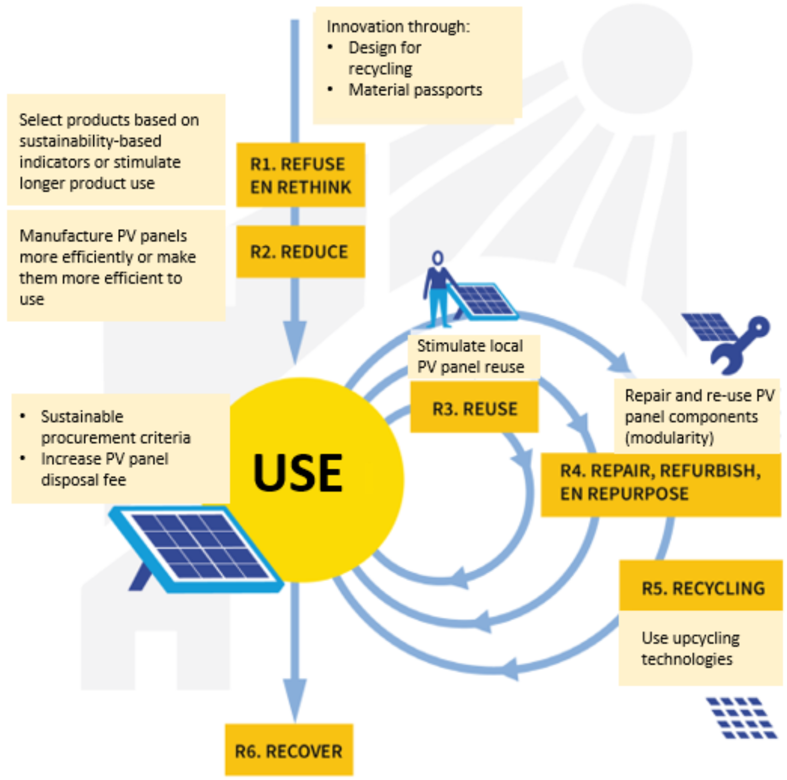

FIGURE 7.2 OVERVIEW OF THE IDENTIFIED SOLUTION DIRECTIONS TO INCREASE PHOTOVOLTAIC PANEL CIRCULARITY AND CIRCULAR END-OF-LIFE MANAGEMENT ACTIVITIES, BASED ON THE R-LADDER FOR CIRCULAR STRATEGIES. DESIGN FORMAT COPIED FROM BEEFTINK & BERGSMA (2021: P 19)

8. DISCUSSION

In this chapter, the research findings are discussed in a wider scope. First, the applicability of socio-technical system theory is discussed. Hereafter, the research findings are compared to existing literature. Then, the research limitations are discussed. This chapter is concluded by discussing the implications of the research findings for knowledge users.

8.1 REFLECTION ON THE APPLICABILITY OF SOCIO-TECHNICAL SYSTEM THEORY

The transformation toward a CE requires systematic change. In this research, it is explained that socio-technical systems may resist these changes. Therefore, it is important to identify and understand the systematic nature of factors that hinder system transformation (Aminoff & Sundqvist-Andberg, 2021). This was done in this study via the identification of barriers toward circular PV panel EoL management, which was followed by the identification of solution directions to overcome the identified barriers.

The contemporary system for PV panel EoL management was explained as a socio-technical system, wherein people interact with technology to achieve the purpose of PV panel recycling. To explain path-dependencies and lock-in within the existing socio-technical system around unsustainable technologies, the MLP framework was adopted (Geels, 2007; Loorbach et al., 2017). In this research, special attention was paid to the ongoing dynamics between the regime, or the normal way of doing things, and niche-level innovations that attempt to change this (van Eijck & Romijn, 2008). The regime is sustained by interaction between multi-dimensional barriers (Raven et al., 2010). In the case of Amsterdam, the results showed that the normal way of doing things is likely to result in substantial losses of critical materials. However, most PV panels are yet to be installed, which indicates that there is still time and opportunities to change the system for their management at EoL. This study makes an interesting theoretical contribution as understanding why the existing system for PV panel EoL management is locked-in around downcycling technologies is a critical step towards overcoming the obstacles to system innovation (Aminoff & Sundqvist-Andberg, 2021). Here, a lot of overlap was found with barriers that were identified in socio-technical analyses of WEEE systems in other European Union countries. Not only referring to barriers related to existing infrastructure or the design of WEEE products but also to similar issues in the organization of EPR schemes (Aminoff & Sundqvist-Andberg, 2021; Zacho et al., 2018). In all cases, the current system for WEEE management is found to be operating to recycle waste and can thus be described as an 'end-of-pipe' approach (Zacho et al., 2018). This is not an issue perse but rather raises the question of how elements within the existing system can be modified to increase its performance and include other, more sustainable activities. For example, implementation of reuse activities when returned PV panels are meeting performance criteria and still have a life length that is worthwhile (van der Heide et al., 2021). In this sense, the alternative design of PV EoL management also has upstream consequences for overall production and consumption patterns (Zacho et al., 2018). From a CE perspective, PV panel EoL management offers an interesting context to study these dynamics, as both the technologies and political pressures to improve circularity and resource efficiency already exist. Moreover, it can be argued that the system is already changing due to the growing need for critical materials. These materials are lost in contemporary PV recycling activities, which creates windows of opportunity for system modification via innovative technologies and practices and legislative pressure (van Exter et al., 2021).

SNM theory stresses that real-life experiments play a key role in the establishment of innovative technologies and practices. Innovation was described within the context of niches: protected spaces wherein users are willing to support emerging innovations and that is therefore important in realizing system transformations (Geels, 2004). According to Raven et al. (2010), innovation of technologies and practices is not seen as a straightforward process due to the presence of multi-dimensional barriers that sustain the existing system. This is also why upcycling technologies can be considered hopeful monstrosities, as they are likely to support circular PV panel EoL management in the long-term but provide crudely within the existing system (Schot and Geels, 2008; p 537). However, it can also be argued that the presence of multi-dimensional barriers creates opportunities for innovation. For example, the realization that EVA encapsulation resulted in limited recyclability stimulated exploratory initiatives such as design for recycling. Cities were indicated to be promising environments for niche-level developments due to the geographical proximity of stakeholders and their multidisciplinary interaction (European Commission, 2019). However, niche-level developments for circular PV panel EoL management and PV panel circularity, in general, are found to be mainly happening on a national or even a European scale through collaborations with a broad range of stakeholders. This is understandable given that both PV panel design and production and EoL management do not take place within the context of cities. However, cities can still play an interesting role through the facilitation of local reuse networks. Kemp et al. (1998) stress that niches become empowered when expectations become more accepted or when networks of actors become larger. However, it was found to be very complex to translate the identified solutions in terms of the three key SNM processes: actor-network activities, people's learning processes, and the dynamics of their expectations (van Eijck & Romijn, 2008). This is because the transition towards circular PV appears to be still in an early phase and identified activities to increase PV circularity throughout the PV supply chain in the Netherlands still consist of a loose set of laboratory experiments. Nonetheless, the research findings did find developments that suggest niche-level empowerment in the Netherlands such as the formation of the FAIR SOLAR network (2021). An organization that pushes for a circular Dutch PV sector by bringing together all actors that want to take steps towards more circular and fair solar energy, and that includes governmental organizations, research institutes, experts, and other enthusiasts. The results indicate that to transform the socio-technical system for PV EoL management, internal system transformation needs to be complemented by external interventions. In this sense, a future model for PV EoL management is ultimately shaped by the overall aim and visions of key stakeholders involved. System transformation depends highly on the aims of these stakeholders, which is to create business and economic value or include more societal and environmental aspects into their vision for PV panel end-of-life management. This underlines the importance of agency and that system change may ultimately require new actors, regulations, and organizations (Zacho et al., 2018).

Lastly, the system for PV panel end-of-life management can also be considered as a niche in itself. From this perspective, PV EoL management operates as a sub-system that is part of a larger transition towards sustainable energy generation or a circular economy. This also relates better to the idea of sustainability transitions, which are driven by disruptive and far-reaching changes that affect multiple dimensions (Loorbach et al., 2017). While this decreases the general applicability of the MLP as a framework in this research, the MLP still provides a valuable framework for thinking about socio-technical system dynamics and system transformations over time.

8.2 REFLECTION ON FINDINGS IN RELATION TO THE EXISTING LITERATURE

The systematic literature review results identified the necessity to increase the circularity of PV EoL management by the implementation of innovative reuse strategies and upcycling infrastructure. Here, knowledge gaps were found on the conditions that must be met to make high-value recycling methods competitive with contemporary recycling practices, how policies can be improved and implemented to manage emerging PV waste streams, and under what conditions PV panel reuse can complement PV recycling and how to make PV panel reuse more attractive for consumers in general. This section will reflect on the results of the conducted research and adress these identified knowledge gaps.

The academic literature reviewed suggested that PV panel reuse within the same function appears to be mainly feasible above a threshold of 70% module performance and a life length that is worthwhile (van der Heide et al., 2021). The results add-on these findings and address the knowledge gap under what conditions reuse is an interesting strategy to complement PV recycling, by identifying that PV panels that meet conditions for direct reuse mainly come from premature removal from large-scale installations, such as professional solar parks. This is because a large amount of PV panels in these types of installations make it more attractive to consider early replacement based on economic lifetime and financial returns (Stichting OPEN, personal communication, May 25, 2022). Early removal in these types of installations is found to be further stimulated by the rapid development of PV technology production rates and affordability (Beeftink & Bergsma, 2021). This indicates that there are possibilities to promote direct PV panel reuse via setting-up local collaborations with these types of installations, which an promising development. Especially when taking into acount that there is a growing need for appropriate business models to promote PV panel reusability (Salim et al., 2019). It can also be argued that it is difficult to reuse individual PV panel components due to contemporary PV panel design. Therefore, it is likely that business models concerning reuse of c-Si PV panels will be mainly focused on direct reuse activities.

This relates to the knowledge gap on how to make PV panel reuse more attractive for consumers. Ideally, PV panel reuse is not solely driven by economic incentives but also considers social or environmental aspects. Here, the identified PV panel reuse project that is currently being set up in Amsterdam Zuid-Oost by ZonNext serves as a promising example for an alternative view on sustainable business models. This is because this project also explores more the more social dimension of PV panel reuse. Which, when applied under the right conditions, could help with the mitigation of the energy-poverty gap by widening the access to sustainable energy sources. PV panel reuse within the same function was found to be less likely in the case of private users, as in these types of installations PV panels are assumed to be active for a longer period, which decreases their direct reuse potential (Circular material consultancy, personal communication, March 5, 2022). Implementation of other reuse strategies, such as the reuse of individual PV panel components, is found to be hindered by contemporary PV panel design (Radavičius et al., 2021). Nonetheless, technological developments in PV panel design and production, such as modular design, have the potential to increase the reusability of the next generation of PV panels. Moreover, the tendency to only reuse PV panels that meet performance criteria can be complemented by promoting out-of-the-box solutions. For example, this research finds that there are also possibilities to reuse outdated PV panels in a different function (FAIR SOLAR netwerk, 2021). While this is not a solution that is likely to be applied on a large scale, it does support the view of EoL PV panels as a resource rather than a waste. This links to a waste-to-resource approach that considers PV panels as a valuable resource that can still produce sustainable benefits for a range of actors (Sica et al., 2018). However, both life-extension of existing panels and redesign of future panels do not form the solution for circular EoL management of the 1st generation of emerging PV panel waste streams. The solution for the 1st emerging PV waste streams therefore needs to be found in establishing better recycling activities. Nonetheless, life extension in general has no negative environmental effects (van der Heide et al., 2021). Thus, life-extension strategies can also be used to give upcycling facilities more time to establish.

The research results verify the findings made in the systematic literature review that the prevalence of downcycling activities is caused by the limited return quantities of PV panels along with contemporary PV panel design using EVA encapsulation (Deng et al., 2019; Salim et al., 2019). Low volumes of returning PV panels not only make recycling activities more expensive but also negatively affect manufacturer incentives to proactively engage in recycling schemes (Franco & Groesser, 2021). Additionally, research findings confirm that is likely that a growing number of EoL PV panels will

encourage the development of better recycling infrastructures in the coming decade (Deng et al., 2019). The results add on these findings. and address the related knowledge gap, by emphasizing the role of WEEE legislation in hindering the competitiveness of high-value recycling methods compared to contemporary recycling practices. This indicates that there is a need to change WEEE recycling targets by basing these targets on material value instead of weight (Beeftink & Bergsma, 2021). Changing WEEE legislation is found to be a promising way to promote more favorable conditions for high-value recycling technologies implementation. As the research findings indicate that WEEE targets based on weight are locking WEEE operators into minimum standards for PV panel recycling and hinder innovation efforts. This is becausse WEEE operators are already meeting their targets for WEEE recycling, which weakens incentives to increase disposal fees. Also, WEEE operators can meet their recycling targets by solely applying downcycling activities. Additionally, the investment costs in the existing recycling infrastructure seem to further sustain the existing system for PV panel EoL management. This affects the commercial feasibility of future-proof recycling infrastructure. Therefore, there is a need for better use of policy to manage emerging PV panel waste streams and to facilitate system change.

8.3 RESEARCH LIMITATIONS

This section discusses the research limitations and how this might have influenced research outcomes. First, the literature review methodology is discussed. Then, the data collection methods used to generate the results are analyzed. Hereafter, the limitations of the applied data analysis methods are discussed.

While the performed literature review is found to be a robust and reproducible way to generate existing literature on PV EoL management practices, it is still subject to limitations. The systematic literature review provided the basis for this research by assessing existing literature on circular strategies to improve PV panel EoL managent and identifcation of knowledge gaps. Therefore, the biases and limitations of the performed literature review could substantially affect the main results of this research, as identification of other knowledge gaps could have resulted into a different research aim and research set-up. First, there is the risk of bias in locating studies, given that only the database Scopus was used. Therefore, there is a risk that a relevant body of literature is left out of the initial list of literature generated. This risk is also present when critically assessing the applied search criteria. While the search criteria were selected based on keywords that were often used in literature in a first exploratory search, there is still a risk that relevant articles were left out that used slightly different keywords to discuss similar topics. Limitation of the search criteria to the period 2012-2022 also produced a biased sample for similar reasons. Additionally, there is also a personal bias in article selection, given that articles were initially screened for eligibility by the reviewer. This bias could be reduced via a second researcher that follows a similar producedure and by comparison of the selections afterwards. However, given that this is an individual thesis paper, this action could not be performed. Also, it must be acknowledged that the limited number of 12 scientific articles included also impacts the capacity for generalization of the literature review findings. Lastly, this generalizability is further limited as no distinction was made between different PV technologies and specific circumstances of countries.

Reflecting on the data collection methods, a relatively small group (8) of experts was interviewed. This could influence the research results as identified stakeholder groups can be underrepresented or missing. For example, PV panel recyclers have not been interviewed since it was found that PV recycling is mainly happening abroad. However, insights on PV panel recycling practices were still included in the research via interviews via other parties that are closely affiliated, such as Stichting OPEN. Additionally, (de-)installation companies and public collection points have not been interviewed. However, the experts that were interviewed for this research are all considered to be important and knowledgeable actors within their area of expertise. Therefore, it is argued that the limited amount of expert interviewed has less of an impact on the main research findings compared to limitations mentioned for the systematic literature review. This is supported by the selection of interviewees based on their knowledge of a specific aspect of PV panel EoL management: PV panel production, PV panel WEEE management, legislation, and alternative PV panel design and recycling technologies. The quality of the primary data collected for analysis was further verified by questioning interviewees if there are other specific experts, companies, or organizations that needed to be included in this research based on the asked questions. In most of the interviews, the interviewees claimed that the list of targeted companies and organizations appeared to be sufficient. An exception was found in one interview where an expert was suggested that is knowledgeable on the topics of PV panel recycling practices and upcoming technologies. Unfortunately, this expert responded that he was too busy. However, a newspaper article in which this specific person was interviewed about these topics was still included in the research. The affirmed sufficiency of targeted companies and organizations by the interviewees can be explained by that the field of PV panel EoL management is still relatively small in the Netherlands. This is because PV panel return streams are still limited and that the majority of PV panel EoL management is currently happening in Belgium, France, and Germany. However, there are signs that PV panel EoL management in the Netherlands is gaining momentum. An example hereof is the occurrence of articles in Dutch newspapers on PV panel EoL management (see Bakker, 2022). Additionally, the credibility of interview data was also verified and complemented by secondary data collection methods, including document analysis and sporadic inclusion of newspapers and websites. The choice for using multiple data-collection methods was made to increase the quality of the research findings.

The main type of documents that were used in this research were reports from the municipality of Amsterdam and reports from, or in collaboration with, research institutes and the PV industry. A limitation of document analysis is biased selectivity, given that these reports were not structurally selected but have been suggested by interviewees or were included based on desk research. There is a risk here that the reports included reflect the agendas of the companies that created the report. This is not seen as a major disadvantage as the included documents provided a wealth of additional information that has been used to verify, complement and add-on research findings. However, this research still attempted to mitigate this risk by including multiple reports from a variety of organizations. Therefore, the method for collecting secondary data is considered to have less of an impact on the main results compared to the primary data collected. This is also because a part of the reports collected were suggested in the interviews. In this sense, the interviews conducted also affect the secondary data collected. However, it is important to note that the research scope on PV panel EoL management within the Dutch context entails that a wide variety of secondary data on experimentation on the European or even global scale to increase PV circularity was not collected and included in this research. Nonetheless, examples of important developments happening on the European scale were sporadically mentioned when necessary. For example, the experimentation with recycling technologies by foreign WEEE operators, such as Veolia active in France, or Reiling active in Germany.

Reflecting on the limitations of the data analysis methods, a limitation of the quantitative analysis of PV panel waste streams in Amsterdam is found in the limited data available on the amount of PV panels installed in Amsterdam. Therefore, historical, and future installed PV capacity was estimated based on

dividing MW by average PV panel production capacity. While this still provides a general idea for the increase of PV panel installations in Amsterdam, it does not provide information on the types of PV panels that were installed. This directly affects the validity of the quantitative analysis results regarding the accuracy of the predicted types and sizes of PV waste streams. Also, data on the actual lifetime of PV panels registered at the National WEEE register (2020) does not yet exist due to a limited number of PV panels returned. Thus, an estimated PV panel lifetime of 20 years has been used instead. While this average lifetime was verified via multiple sources, including interviews and industry reports, it still forms a limitation for calculating the emergence of PV material waste streams. This is because the use of life span averages increases the uncertainty for estimating the period when PV waste streams will start to increase in Amsterdam. This is also due to the uncertainties regarding economical versus technical lifespan, as it was shown that the average PV panel lifetime varies per actor. For example, interviews pointed out that companies that have a larger number of PV panels are more likely to replace them based on their economical lifespan. While private individuals are more likely to hold on longer to their PV panels due to the (de-)installation costs (Circular material consultancy, personal communication, March 5, 2022).

Considering the applied stakeholder analysis methodology, research limitations can be found in that not all steps in Enserink et al. (2010) are performed. While an initial overview has been made for the determination of interests, objectives, and problem formulation, this overview has not been verified or evaluated. Additionally, the final two steps in Enserink et al. (2010) for stakeholder analysis are not mentioned in this research report and were also not performed. This refers to the mapping out of interdependencies between actors and the determination of consequences of these findings regarding the original problem formulation. However, the stakeholder analysis mainly served the purpose to explain the functioning of the system for EoL PV panel management by identifying the formal relations between the stakeholders involved. This was already satisfied through the creation of a formal chart that showed stakeholders involved and mapped their formal relations. Hereafter, key stakeholders were interviewed to verify analysis findings and support the identification of barriers and solution directions for a circular system for PV panel EoL management. Thus, not all steps suggested in Enserink et al., (2010) were deemed necessary. It is difficult to compare the impact of the limitations of the applied stakeholder analysis methods on the main results to the quantitative analysis methods. This is because the methods affect separate result sections. Nonetheless, it can be argued that that the limitations of the quantitative analysis have a bigger impact on the results due the susceptibility to other PV panel technologies and PV panel lifespans, which would directly translate into different results.

Limitations of the interview data analysis are found in that no distinction was made between interviewee answers. This could influence the main results as a PV panel producer knows less about the system for collection and processing PV panels than a PV panel collector. However, since the interviews were semi-structured, emphasis was placed on interviewee expertise. Also, the interviews were conducted using a list of guiding interview questions. This list was predefined and sent to the interviewees in advance. Therefore, the researcher might have engaged the interviews with a slight bias that could have affected the type of answers received. However, this was also the reason that SSI methodology was applied, to make sure that each interview could be steered towards topics in accord with the expertise of the interviewee. Moreover, interview coding is a subjective process through the setting-up of analysis categories by the researcher into an analytical guide. Since this analytical guide was used by the researcher itself to code passages in interview transcripts, there is the risk of confirmation bias. It was attempted to decrease the degree of confirmation bias by discussing the analytical guide and individual analysis categories with one of the research supervisors. Therefore, the applied methods for interview analysis are considered to also form less of an impact on the main results compared to the methods of the quantitative analysis.

8.4 IMPLICATION FOR KNOWLEDGE USERS

Based on the identified barriers and solution directions, it is possible to list prerequisites that need to be in place for reuse and upcycling technologies to be incorporated into the existing system for PV EoL management. To meet these prerequisites, different actions are required from different stakeholders. This section will discuss these actions and the implications that they have for the key stakeholders identified: Stichting OPEN, PV producers, WEEE collection parties, and the municipality of Amsterdam.

Stichting OPEN has been identified as a key stakeholder for PV panel EoL and WEEE management in general as they execute EPR on behalf of all PV producers in the Netherlands. First, the research findings indicate that it is crucial to reshape the finance mechanism for charging disposal fees to PV producers by including future accountability. This allows for the setting-up of removal funds that facilitate the incorporation of PV panel reuse and upcycling facilities. It is argued here that it is both logical and fair to base removal funds on the amount of PV panels that a producer puts on the market, instead of the amount of PV panels that are removed. This is because future accountability makes the system for PV panel EoL management more sustainable and resilient toward emerging PV panel waste streams. Given that the current disposal fee averages 12 euro cents per panel, there is a lot of room for improvement without seriously impacting PV panel price. Additionally, it is also found to be important to increase the resource efficiency of EoL activities by lobbying for WEEE targets that are based on value instead of weight. Moreover, Stichting OPEN can increase the length of tender contracts, which would provide WEEE operators with more certainty on their future license to operate. This is beneficial as it improves the willingness of WEEE operators to invest more in technologies or practices that improve reuse and upcycling potential. However, it is also important to pay attention to activities happening on the European scale to prevent replicability and a waste of funding resources. Furthermore, reuse activities must be prioritized over recycling practices. In this sense, the recycling route should only be chosen when collected PV panels do not meet predefined reuse criteria.

The research findings indicate that PV panel producers play a significant role in the system by their influence in the decision-making processes of Stichting OPEN and the type of PV panels that they put in the Dutch market. These both relate to the necessity of increasing the sense of responsibility that PV panel producers have regarding their products. Producer responsibility can be understood as the responsibility to actively consider what impact your products have. This should not only be considered in terms of financial impacts but also by incorporating more CE-oriented perspectives that account for environmental impacts. In terms of PV panel design, recyclability must be promoted by focusing on technological developments such as design for recycling (DfR) and modularity. However, given the large degree of competition in the PV market, it is realistic to state that the inclusion of environmental impacts would also require external pressures to create sustainable business cases. Here, the CBAM in Europe for 2026, which creates carbon pricing on imported products, is a very promising development that acts as an external pressure to increase the sustainability of PV panel management (European Commission, n.d.). The inclusion of criteria based on product circularity would further improve the effectiveness of legislation. Thereby not only increasing the circularity of PV panel EoL management but also decreasing the risk of greenwashing (Solarge, personal communication, April 5, 2022). Moreover, this development could also support the realization of material passports to label PV panels according to their material composition and corresponding environmental impact or footprint.

WEEE collection parties are shown to perform the logistics between PV panel collection points and PV panel recycling. WEEE collection parties are commissioned by Stichting OPEN, and their activities are therefore also linked to the ambitions of Stichting OPEN. The results have shown that there are many contract-based collection parties in the Netherlands. This suggests that there is a degree of competition between individual WEEE collection parties, which can ultimately impact the quality of PV panel EoL management. However, if contracts for these parties are lengthened and this is complemented by prioritization of reuse over recycle activities, WEEE collection parties can play a bigger role in PV panel EoL management. This role is further stimulated by the increasing demand for second-hand PV panels due to issues of material scarcity (WEEE Nederland, personal communication, May 24, 2022).

Lastly, it is also important to address the research implications for Amsterdam. The research findings pointed out that cities currently do not play a significant role in contemporary PV panel EoL management, However, there are interesting opportunities for cities to increase PV circularity by supporting local reuse initiatives and sustainable procurement. Local reuse activities are promising because they reduce the environmental impact associated with PV panel production and transportation of EoL panels. This also works the other way around: since the PV panels have already been produced, second-hand use results in a net-positive environmental impact. It is found that it is particularly interesting to link local reuse initiatives to large-scale installations of PV panels. As in these types of installations, PV panels are more likely to be replaced based on economic lifetime and financial returns, which increases the reuse potential of the removed PV panels. Additionally, it also found that the promotion of local reuse activities has the potential to decrease social inequality and energy poverty. Here, it is important to critically assess under what conditions PV panel reuse is beneficial compared to setting-up financial structures or subsidies for new PV installations that have higher energy production rates. This is because roughly 40% of the costs are found to result from the PV panel itself and the remaining 60% is primarily made up of installation costs.

9. CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the research findings are compared to the research goals by answering the main research question "*What are the barriers and promising solution directions for circular end-of-life management of photovoltaic solar panels located in Amsterdam*?". This is done by structurally answering the sub-research questions 1-4. Hereafter, recommendations for the city of Amsterdam to promote local PV circularity are provided. This research is concluded by setting-out recommendations for future research.

9.1 CONCLUSIONS

The first sub-research question served to contextualize the necessity for circular EoL activities. The answer to this question "*What is the estimated size of photovoltaic panel waste streams in Amsterdam for the period 2022-2050?*" is given by the quantitative analysis of end-of-life (EoL) PV panel waste streams. The results show that for Amsterdam to reach its goal to leave no roof unused by 2040, substantial increases are required in the installation of additional PV capacity in the coming 20 years. It is estimated that if the growth trend for PV panels installed in Amsterdam over the past five years linearly continues towards 2040, there is a deficit of 1.12 million panels to achieve the city its goal of leaving no suitable roof unused. Based on the predictions made for installed PV capacity, it is estimated that photovoltaic (PV) panel waste streams in Amsterdam will start to accumulate in 2031 and will substantially increase in size from 2037 onwards if an average lifetime of 20 years is used. In 2031, the total mass of waste streams is estimated to be 170 tons, which will increase further to 8,863 tons in 2040 and will range between 27,366 and 36,477 tons by 2050. Glass is estimated to be the largest PV material waste stream, as it takes up 70% of the mass. Other PV material waste streams are aluminum (15%), polymers (10%), silicon (5%) and silver (0,1%). While silver only presents 0,1% of the volume, it accounts for roughly 65% of the material value, which is estimated to accumulate to 17.8-23.8 million euros by the year 2050.

The second sub-research question "*How is the system for end-of-life management of photovoltaic panels currently organized?*" more specifically focused on the identification of the stakeholders and their role within the contemporary system for PV panel EoL management. It is found that cities currently do not play a significant role in this system. Instead, the collection and processing of EoL PV panels is organized as a national system, where the organization of extended user responsibility (EPR) plays a crucial role. This is because EPR requires PV producers to establish, finance, and also facilitate the collection and processing of PV panels at EoL. Stichting OPEN is appointed as the responsible actor for execution of EPR on behalf of all producers in the Netherlands. Therefore, Stichting OPEN plays a leading role in the organization of collection and EoL processing of PV panels and WEEE in general. Stichting OPEN enforces EPR by charging disposal fees to PV panel producers and uses these funds to contract collection points and collection companies, and to set up contracts with recyclers. Obsolete panels are currently collected by individual contractors and exported to foreign recycling facilities in Belgium or Germany. In these recycling facilities, the vast majority of PV panels are pulverized into low-grade building materials or used as fuel in incinerators. This verifies that contemporary PV panel EoL management of PV panels on Amsterdam rooftops is likely to result in substantial losses of valuable and critical materials.

The third research question *"What are barriers for circular end-of-life management of photovoltaic panels?"* aimed to enhance the understanding of the individual factors that lead to the prevalence of downcycling technologies in the national system. The research findings identify multiple barriers that interact to form lock-in around existing and unsustainable technologies for PV EoL management. These barriers are categorized as infrastructure and technological, organizational, institutional, supply-chain related, and economical barriers:

- Infrastructure and technological barriers reside in that upcycling technologies find it difficult to compete with low-value recycling activities due to issues of scale. This is also due to the use of EVA encapsulation in contemporary PV panel design, which promotes durability and lifetime but hinders product recyclability at EoL. Also, PV panels are currently not labeled, which decreases the efficiency of recycling processes.
- Organizational barriers are found in the organization of EPR and specifically in the height of disposal fees. The current size of disposal fees is far from sufficient to facilitate high-quality recycling activities for PV panels, which is stimulated by a lack of future accountability in the EPR finance mechanism.
- Institutional barriers stem from recycling targets that are based on weight instead of value. This demotivates incentives to change the existing system as PV panel producers and recyclers are already complying with WEEE standards for minimum recycling percentages. Another institutional barrier is the design of subsidy grants. These tend to focus on generation capacity instead of PV panel circularity, which stimulates the replacement of PV panels based on economical rather than technical lifetime.
- Supply-chain-related barriers reside in the lack of collaboration throughout the PV supply chain. First, results indicate that there is a lack of collaboration between PV panel manufacturers and PV panel recyclers. Second, there was found to be competition between WEEE collection parties.
- Economical barriers are found in that product price, instead of product sustainability, is considered a key factor for PV panel procurement along with product lifetime and production capacity. Also, quantities of returning PV panels are currently too low for upcycling technologies to be considered economically feasible. Lastly, the use of EVA encapsulant in PV panels also hinders cost-effective upcycling.

The final sub-research question *"What are promising niche-level developments and practices in the Netherlands to upscale circular end-of-life activities for photovoltaic panels?"* served to identify the ongoing activities in the Netherlands that can act as solution directions to overcome the identified barriers. It is suggested that an increase in PV circularity at EoL is inextricably linked to the earlier phases of the PV supply chain. Therefore, the identified innovations and practices are framed as sub-niche experiments along the PV supply chain in the Netherlands. These developments involve a broad range of actors, which ranges from PV panel manufacturers, users, and producers to public authorities. The most important technological developments to increase the circularity of PV EoL management focus on changing PV panel design, material passports, and implementation of upcycling technologies. Here, the choice for circular PV can be stimulated via sustainable procurement criteria, while upcycling technologies can be stimulated by increasing PV panel disposal fees. However, these developments become less relevant when considering the city-scale, as cities are found to be predominantly concerned with the PV panel user phase. The research findings indicate that opportunities to increase

PV circularity in cities mainly resides in experimentation with local reuse initiatives. Experimentation with local reuse is an attractive circular strategy to promote PV panel life-length and has the potential to broaden access to sustainable energy. Here, it is especially interesting to look for collaborations with large-scale PV panel installations. PV panels in these types of installations are more likely to be replaced based on economic lifetime and financial returns, which increases the reuse potential of the removed PV panels. Furthermore, local reuse initiatives provide a promising context for experimentation with reuse-based business models and can facilitate learning practices.

To conclude, while the present conditions are found to create windows of opportunity to modify the existing system via the identified solution directions, external intervention is also required. A future model for PV EoL management is ultimately shaped by the overall aim and visions of the stakeholders involved. System transformation depends highly on the aim of these stakeholders, which is to create business and economic value or include more societal and environmental aspects into their vision for PV panel end-of-life management. In the case of Amsterdam, this ultimately translates to the willingness of the city to combine its energy transition with its circular economy ambitions by empowering initiatives and out-of-the-box solutions that combine both ambitions and support a circular solar energy transition. The next section provides a first step here for by providing a list of recommendations to increase PV circularity in Amsterdam.

9.2 RECOMMENDATIONS FOR THE CITY OF AMSTERDAM

This section provides a list of recommendations for the city of Amsterdam to promote and support a circular solar energy transition based on the research findings. Note that this list is not exhaustive and primarily serves to stimulate the municipality and citizen initiatives.

- Make an overview of large-scale PV panel projects within the region and explore partnership possibilities
    - It is especially interesting to look for local collaborations that can broaden access to solar energy and thereby decrease the risk of energy poverty
- Create an inventory of promising locations for installation of second-hand PV panels within the city that meet the following criteria
    - The location has a suitable roof (type, quality, and surface) for PV panel installations
    - The energy-demand can be covered by expected production of solar electricity
    - The location is available for a period of <5 years*
- Set-up collective buyer schemes based on sustainable procurement criteria
- Promote procurement of sustainable PV panels by providing information on PV panel circularity via websites or similar tools
- Improve monitoring of PV panel material streams via registration of the types of PV panels that are installed
- Set-up a local raw material database to monitor PV panel material streams
- Create a competition for designing out-of-the-box solutions to reuse PV panels in a different function
    - This is especially relevant for older PV panels that would otherwise be transported for recycling
- Lead by example.
    - For example, install sustainable PV on municipality buildings and promote this

*This criterion is not a prerequisite for PV panel reuse, but it makes the choice for second-hand panels more attractive compared to installation of new and more costly PV panels that have a higher production capacity.

9.3 FUTURE RESEARCH

First, future research could improve on the quantitative analysis results for future PV panel waste streams by including more scenarios for PV panel installation, such as more detailed energy scenarios. An example hereof is given in Carrara et al. (2020), where the scenarios for material demand for wind and solar PV take into account four factors: power generation capacities, plant lifetime, sub-technology market shares, and material intensity. Additionally, future research can also focus on adding more indicators besides mass and material value, such as material impact. Furthermore, other Dutch cities can be included to verify, complement, and add to existing findings.

Second, future research can also improve the understanding of the interaction dynamics between barriers in the contemporary system for PV panel EoL management. It could be interesting to analyze if similar barriers are identified for other WEEE products or in other contexts within the Netherlands, such as textile recycling. This is because PV panel EoL management is shown to have special contextual characteristics and is strongly driven by EPR schemes. Therefore, future research that compares the identified barriers with another context could be beneficial to see to what degree the factors that contribute to system lock-in are contextually driven. Additionally, quantitative analysis can also enhance insights regarding the significance of the individual barriers. This could result in a priority list, which makes it more tangible to see what barriers need to be addressed first to improve PV circularity.

Thirdly, the identification of solution directions to improve the circularity of PV panel EoL management was only done within the context of the Netherlands. Therefore, future research is also required to include the activities happening on the European scale. This will provide a more comprehensive picture of the possibilities to overcome the factors that sustain the use of unsustainable technologies. Furthermore, international cooperation could improve the efficiency of PV panel EoL management and prevent unnecessary waste of resources. For example, by preventing the need for pilot testing of technologies that have already been evaluated in other countries.

Lastly, future research on local reuse initiatives is necessary for a better understanding of the possibilities to support circular PV EoL management in cities such as Amsterdam. In the context of this research, local reuse initiatives can be analyzed according to the three key processes of SNM: actor-network activities, people learning processes, and the dynamics of their expectations. This also provides a better understanding of the role that citizens can play in facilitating system change. Furthermore, research on local reuse initiatives can create opportunities for a circular energy transition and at the same time widen the access to sustainable energy production.

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APPENDIX A. SEMI-STRUCTURED INTERVIEW DOCUMENTS

A.1 EXAMPLE CONSENT FORM

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [21/04/2022], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves being recorded using either video recording (if online) or audio recording (if physical)	☐	☐
4. I understand that recordings will be destroyed after the completion of the thesis. The study will end approximately in mid-July 2022.		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
5. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: • Anonymization of interview transcripts • Data storage on the personal drive of the researcher • Deletion of name and contact address after completion of research	☐	☐
6. I understand that personal information collected about me that can identify me (name and email), will not be shared beyond the study team.	☐	☐
7. I understand that the (identifiable) personal data I provide will be destroyed when the research is concluded (approx. mid-July 2022).	☐	☐

C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
8. I understand that after the research study the de-identified information I provide will be used for data collection to generate expert insights and validate findings concerning the master thesis report of Mathijs Stokvisch	☐	☐
9. I agree that my responses, views, or other input can be quoted anonymously in research outputs	☐	☐
D: (LONG-TERM) DATA STORAGE, ACCESS AND REUSE		
10. I permit the anonymized transcripts that I provide to be archived on the personal hard drive of the researcher for 5 years.	☐	☐
11. I understand that access to these transcripts is private. Transcripts are not placed in an open repository and can only be accessed by the research team.	☐	☐

Signatures

________________________ ____________________ ________

Name of participant [printed] Signature Date

I, as the researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands what they are freely consenting.

________________________ ____________________ ________

Researcher name [printed] Signature Date

Study contact details for further information: Mathijs Stokvisch

A.2 INTERVIEW QUESTIONS

Interview stage (Adams, 2015).	P1: Introduction
Introductory questions	Kan u wat vertellen over uzelf en uw functie?
	Hoe werkt uw organisatie aan hergebruik, recycling of andere vormen van end-of-life verwerking van zonnepanelen?
	Hoe kijkt u aan tegen de grootschalige plaatsing van zonnepanelen in Nederland en de vervangingsopgave hiervan?
Wrap-up	P2: End-of-life management: actor and institutional analysis
Wrap-up	Welke actoren zijn momenteel betrokken zijn bij het verwerken van afgeschreven zonnepanelen en hergebruik in Nederland?
	Hoe zijn de verantwoordelijkheden voor de verwerking van zonnepanelen verdeeld onder deze actoren?
	Welke actor of actoren moet circulair verwerken van PV-afval stimuleren en hier verantwoordelijkheid voor nemen?
	Hoe moet(en) deze actor(en) dit doen?
	P3a: Technical constraining and stimulating factors for circular end-of-life management
	Wat zijn vanuit een technologisch perspectief beperkende factoren/ uitdagingen voor het hoogwaardig verwerken van afgeschreven zonnepanelen en hergebruik in Nederland?
	Wat zijn momenteel de grootste technologische ontwikkelingen in Nederland voor het hoogwaardig verwerken van zonnepanelen? E.g. design for recycling
	P3b: Economical constraining and stimulating factors for circular end-of-life management
	Gekeken naar het kostenplaatje, wat zijn economisch beperkende factoren voor het hoogwaardig verwerken van zonnepanelen en hergebruik in Nederland?
	Wat kunnen economisch stimulerende factoren (financiële stimulansen) zijn voor het Nederlandse bedrijfsleven om hoogwaardig verwerken van zonnepanelen te stimuleren? E.g. inkoopcriteria, vergroten verwerkingsbijdrage, lease-structuren
	Gezien het feit dat veel hoogwaardige verwerkingstechnieken pas rendabel worden bij grote hoeveelheden zonnepanelen, wat zijn mogelijke businessmodellen om de hoogwaardige verwerking van zonnepanelen aantrekkelijker te maken?
	P3c: Policy-related constraining and stimulating factors for circular end-of-life management
	Is het huidige beleid, wet- en regelgeving rondom verwerken van zonnepanelen (producentenverantwoordelijkheid) momenteel een beperkende of stimulerende factor voor het hoogwaardig verwerken van zonnepanelen in Neederland?

	Hoe kan beleid, wet- en regelgeving beter worden ingezet om circulaire verwerking van zonnepanelen te stimuleren? E.g. ecolabels (EPEAT)
	Wat zijn de belangrijkste acties of initiatieven die mee moeten worden genomen hiervoor?
	P3d: Social-cultural constraining and stimulating factors for circular end-of-life management.
	Wat zijn beperkende factoren sociaal-culturele factoren voor de ontwikkeling van circulaire zonnepanelen?
	Hoe kan je vanuit een sociaal-cultureel oogpunt, het belang van circulaire zonnepanelen stimuleren?
	P4: Reuse of PV panels as a circular solution route
	Kent u hergebruiksprojecten voor zonnepanelen?
	Is naast hoogwaardig recyclen, hergebruik naar uw mening een veelbelovende oplossingsroute voor de stroom PV-panelen die vanaf 2026 wordt voorspeld te gaan toenemen?
	P5: The role of pilot projects in findings solutions for circular PV panel end-of-life management
	Wat is de rol van pilotprojecten als middel om meer te leren over oplossingsrichtingen voor het circulair verwerken van zonnepanelen?
	Gekeken naar pilots die al aan de gang zijn of in de pijpleiding zitten, zijn er dan nog belangrijke ontwikkelingen en factoren m.b.t het hoogwaardig verwerken of hergebruiken van zonnepanelen die nog niet in dit interview zijn besproken?
	Hoe kan je innovatie en leerprocessen via pilotprojecten verder stimuleren?
	Welke partij moet hier de voorhand in nemen?
	Kent u nog andere personen binnen uw netwerk die interessant en belangrijk zijn om over dit onderwerp mee te praten?
	P4: Conclusion
	Zou u de resultaten van deze studie willen ontvangen?
	Kan ik u contacten voor aanvullende vragen? Met wie zou ik over hergebruik PV in Nederland of pilotprojecten zeker verder moeten praten?

APPENDIX B. WEIGHT-TO-POWER RATIO

Figure B.1 shows the exponential curve fit corresponding to the weight-to-power ratio as calculated in (Weckend et al., 2016). This figure provides an estimation for the increase in PV panel power over the period 1970-2050.

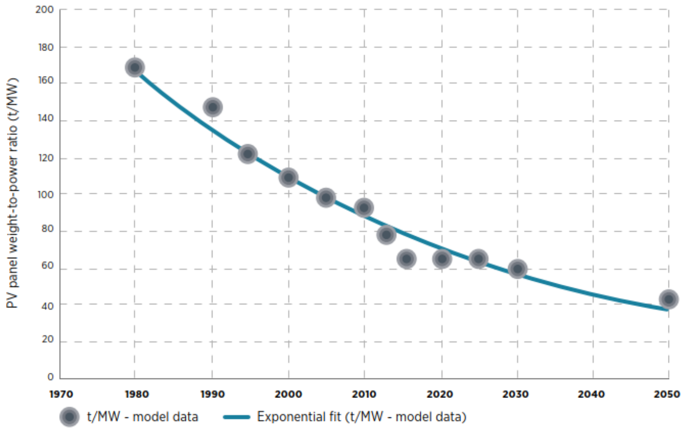

FIGURE B.1. EXPONENTIAL CURVE FIT OF PROJECTION OF PV PANEL WEIGHT-TO-POWER RATIO [T/MW]. SOURCE: (WECKEND ET AL., 2016).

Table B.1 provides an overview of PV panel weight to power ratios for the period 2011-2040 based on the data shown in Figure B.1.

TABLE B.1. OVERVIEW PV PANEL WEIGHT TO POWER RATIO PER YEAR. DATA DERIVED FROM WECKEND ET AL., 2016)

Year	PV panel weight to power ratio [t/MW]	Year	PV panel weight to power ratio [t/MW]
2011	85	2026	64
2012	83	2027	63
2013	81	2028	62
2014	79	2029	61
2015	77	2030	60
2016	75	2031	58.5
2017	73	2032	57
2018	71	2033	55.5
2019	69	2034	54
2020	70	2035	52.5
2021	69	2036	51
2022	68	2037	49.5
2023	67	2038	48
2024	66	2039	46.5
2025	65	2040	45

APPENDIX C. GLOBAL PHOTOVOLTAIC TECHNOLOGY MARKET SHARES

PV technologies are divided into four different sub-categories, where the last three are collectively known as thin-film technologies, due to the limited thickness of the PV cell (Carrara et al., 2020):

- Wafer-based crystalline silicon (c-Si), using either mono- or multi-crystalline silicon
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIGS)
- Amorphous silicon (a-Si)

Figure C.1 provides an overview of the global market share for these PV technologies. This figure indicates that wafer-based silicon technologies have maintained an average market share of 95% over the last few years, with growth in dominance for mono-Si compared to multi-Si technologies. Figure C.2 compares the market share of thin-film technologies, which together comprise 5% of the global market in 2020. Here, especially CdTe technologies are dominant, as they take up 3.7% in 2020. While installation of a-Si technologies continues to decline and is set at 0.1% in 2020. CIGS technologies assume 1.2% in 2022. Additionally, it is important to mention that innovative PV technologies are currently being developed. However, in accord with Carrara et al. (2020), such technologies have been left out of the scope of this analysis given that their market success and large-scale implementation are highly unlikely in the near future.

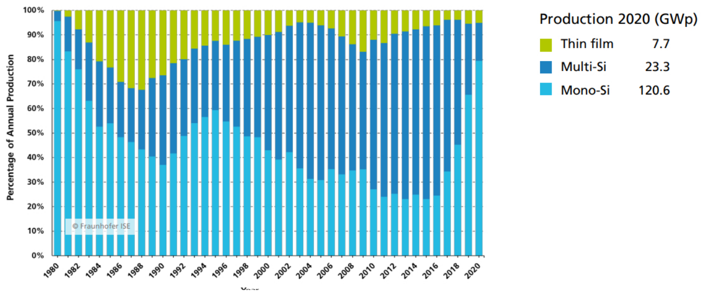

FIGURE C.1. PV PRODUCTION BY TECHNOLOGY: PERCENTAGE OF GLOBAL ANNUAL PRODUCTION. SOURCE: FRAUNHOFER INSTITUTE (2022: P 23)

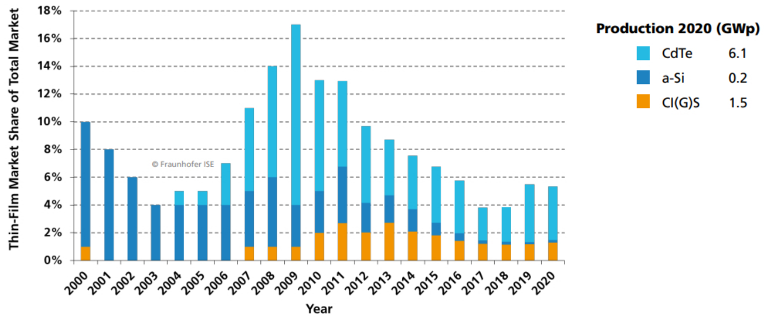

FIGURE C.2. MARKET SHARE OF THIN-FILM TECHNOLOGIES: PERCENTAGE OF GLOBAL ANNUAL PRODUCTION. SOURCE: FRAUNHOFER INSTITUTE (2022: P 24)

APPENDIX D. PROBLEM FORMULATIONS FOR PHOTOVOLTAIC PANEL END-OF-LIFE MANAGEMENT STAKEHOLDERS

Problem formulations of identified PV panel EoL management stakeholders are set out and comparatively analyzed based on stakeholder interests, objectives, existing or expected situations, and causes (Table D.1). Table D.1 also identifies workable solution routes based on problem formulations. This comparative analysis serves as background information that provides additional insights into stakeholder dynamics.

TABLE D.1 PROBLEM FORMULATIONS OF STAKEHOLDERS ACTIVE IN EOL MANAGEMENT OF PV PANELS

Stakeholder	Interests	Desired situation/objectives	Existing or expected situation and gap	Causes	Workable solutions
Stichting Open	Execute producer responsibility on behalf of producers	Organization of low-cost and sustainable collection and recycling of WEEE within legal frameworks	Increase in return quantities of PV panels but the dominance of down-cycling EoL activities	Low waste contribution, current return quantities of PV panels financially inadequate for high-value recycling, free riders that do not pay the waste contribution	Increase waste contribution and create finance mechanism to ensure high-quality EoL processing of PV waste streams
Individual producers and importers	Gain profit from manufacturing or importing PV panels	Maintain sustainable profit margins	PV panel sales increase but weak incentives to increase the circularity of a product	Competition in the PV market is based on product price, with no competition on product sustainability score.	Include sustainability of product in price, smarter design of PV panels
Stichting ZRN	Represent interests of Dutch solar PV Branche members within Stichting OPEN	Low cost and sustainable collection and recycling of WEEE within legal frameworks	PV panel sales increase but weak incentive to increase waste contribution	Contemporary PV recycling is in accord with legal frameworks	Further, extended producer responsibility by extending legal frameworks
PV Cycle	Advocate interests of its former members in Stichting OPEN through ZRN	Low cost and sustainable collection and recycling of WEEE within legal frameworks	PV panel sales increase but weak incentive to increase waste contribution	Contemporary PV recycling is in accord with legal frameworks	Further, extended producer responsibility by extending legal frameworks
PV panel owners	Save energy costs, lower CO2 footprint	Affordable PV panels with high productivity and long-lifespan	Considerable t increases in unsustainable PV panel purchases	The lower price of unsustainable PV panels compared to more sustainable alternatives	Stimulate purchasing of sustainable, ideally circular, PV panels
Deinstallation companies	Gain profit from providing uninstallation services	(De)install as many PV panels as possible	(De)installation of PV panels will increase	Increase in PV panel sales	Engage in PV panel reuse schemes to further promote the number of (de)installations
Public collection points	Provide a central collection point for (e-)waste	Increase awareness and returns rates of WEEE (ideally to > 85%)	PV panel return rates will increase but these will mainly be very old and truly EoL	Private PV panel owners will keep PV panels on roofs if possible or will sell PV panels on the second-hand market	Stimulate handing in of PV panels through collection campaigns
Wecycle	Organizing collection and transportation of e-waste	Execution of low-cost and sustainable collection and recycling of WEEE through contracting collection companies	Collection and transportation of PV panels will increase, but recycling happens mostly abroad	Lack of Dutch recycling facilities due to low quantities of returned PV panels	Set up pilots for high-value recycling of PV panels in NL
WEEE NL	Collection, testing for reuse, and transportation of e-waste and providing consultancy services	Gain more funding from Stichting OPEN to set up pilots for reuse and high-value recycling of PV panels in NL	Collection and transportation of PV panels will increase, but only license for collection and transportation services until March 2026	Appointment of Stichting OPEN as an executive organization for producer responsibility	Create a stronger lobby with Stichting OPEN
Recycling facilities	Gain profit through providing recycling services	The high number of PV panels returned for recycling	PV panel recycling activities are low value (downcycling)	PV panel design based on lifetime instead of recyclability, no incentive for upcycling	Develop high-value recycling techniques, recycling based on value instead of weight
Research institutes	Development of innovative technologies	Developed technologies are adopted and deployed on a large scale	An increasing amount of PV waste stimulates the development of better PV panel design and recycling technologies	The contemporary design of PV panels	Develop circular PV panels and PV technologies to upcycle existing PV panel models