Photovoltaic recycling in Europe: from trash to treasure,

a waste stream forecast

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CoSEM MSc thesis

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In collaboration with EIT InnoEnergy
Supported by the European institute for Innovation and Technology

August 30, 2021

Acknowledgement

This thesis project marks the end of my time as a Complex Systems Engineering and Management student at TU Delft. I would like to sincerely thank my supervisors Ivo Bouwmans and Daniel Scholten for their time, critical feedback and assistance in shaping my thesis project. Their expertise has, without a doubt, greatly raised the quality of my thesis.

Furthermore, I would like to express my gratitude to Javier Sanz, my external supervisor from EIT InnoEnergy, for giving me the opportunity to work on a project that so perfectly fits my personal interests, providing me with a fresh perspective and connecting me with multiple actors in Europe's PV value chain.

Lastly, I would like to thank Yun Luo CEO of Rossi Solar, Lodovico Ramon director of the FRELP project and Bertrand Lempkowicz marketing communication manager at PV CYCLE for providing me with industry specific insights, that I would never have been able to find in the academic literature alone.

Roelof Stam

Executive summary

The solar power capacity in Europe has increased significantly over the last two decades. As Europe attempts to create a low carbon society, it is likely that PV technology will play an ever more important role in Europe's future energy system. As the first solar plants are starting to be decommissioned, enormous amounts of solar modules will soon be added to the photovoltaic (PV) waste stream. In order to reduce waste, conserve natural resources, increase economic security, decrease carbon emissions and save energy, effective PV End of Life (EoL) management is needed. To establish a solid recycling strategy, a good understanding of future PV waste streams is key.

A waste stream forecast can be used to determine the recycling capacity needed in the future, setup the right disposal procedures for hazardous materials, guide effective PV EoL management and examine possible economic profitability of the market. Despite the numerous benefits, to the best of our knowledge, no PV waste stream assessment has been done for Europe in the last decade. To contribute to the current body of literature, this thesis aims to answer the following main research question:

> *What is the economic potential of the PV recycling industry in Europe up until 2050, based on expected waste streams?*

To find a meaningful answer to this research question a PV waste stream forecast model is built in python. Using the model, a scenario-based forecast of the emerging PV waste streams in Europe is made and the economic potential of the PV recycling market is examined based on the notion of 'external' economies of scale. To the best of our understanding, this study is the first to apply a scaling law to analyse the future economic potential of the PV recycling market. Furthermore, based on the results, a number of specific recommendations for future PV EoL management are provided.

The study was conducted as follows. First a concise literature review was carried out, to gather input data for the model and provide an overview of current PV EoL practices. Next, using a Weibull probability distribution annual silicon PV waste streams were estimated for multiple future installed capacity scenarios. Based on the waste stream forecast, the future material value was calculated, taking into account two recycling yield scenarios and fluctuating material prices. Based on a scaling law, using current recycling costs of the Full Recovery End of Life Photovoltaic Project (FRELP) as benchmark, multiple PV recycling cost reduction scenarios were developed. By comparing the recovered material value and the recycling cost estimates, the economic potential of the future PV recycling market was analysed.

As current waste volumes are small, PV recycling is not yet profitable. The results show that annual waste volumes are expected to remain rather insignificant for the first couple of years. However, they are expected to increase greatly over the coming decades. In 2050 the expected annual waste volumes range between 720 kt/y and 1,450 kt/y, depending on future installed capacity.

With an estimated total market value ranging from 8 G€ to 10.5 G€, there is significant potential value in future PV waste. However, it depends on the costs of the recycling process and waste collection rates, whether Europe will actually be able to capitalize on the emerging waste volumes.

The average costs of recycling are expected to decrease as the market grows. Even with modest scaling effects, in a weak cost reduction scenario, recycling costs decrease significantly. The results indicate that there is definitely a good possibility for profitability in the PV recycling market in the future. As waste volumes grow, it becomes more likely that the industry becomes self-sustaining. However, if and when this happens depends on various variables. In a favourable case, this could be as soon as 2023. However, in unfavourable circumstances it could take decades for the PV recycling industry to become profitable.

To increase the probability of profitability in the PV recycling market, waste collection rates should be increased. This can be achieved by obliging the parties responsible to pay fees upfront, covering the costs of disassembling, transportation and recycling of solar modules. Moreover, to decrease transportation costs, decentralized waste collection points or the existing WEEE recycling infrastructure, could be used for pre-treatment of PV waste. Furthermore, as long as waste volumes are relatively low, in order to decrease recycling process costs, centralized recycling should be promoted. Member states are advised to work together and cluster their PV waste.

To further develop a comprehensive European PV EoL strategy, the following topics are suggested for future research. First, further research is needed to figure out if the fluctuations in annual added capacity cause spikes and dips in future solar panel decommissioning. Second, to confirm that pre-treatment is a solid cost reduction strategy, the effects of pre-treatment on the average recycling process costs should be investigated. Third, based on the country specific waste volume estimates of this study, future research could try to find the optimal locations for PV recycling plants in Europe. Fourth, to increase the likelihood of a scenario with strong scaling effects becoming reality, future research could look into regulatory tools to stimulate external economies of scale in the PV recycling industry. Fifth, the effects of 'internal' economies of scale on average recycling process costs of a single facility would be interesting to investigate.

Keywords: Crystalline Silicon (c-Si), Economies of Scale, End of Life Management (EoL), Forecast, Photovoltaic (PV), Solar Panels, Waste Stream, Weibull Distribution

EIT InnoEnergy, The European Solar Initiative

This thesis project is written in collaboration with EIT InnoEnergy. InnoEnergy is an innovation engine for sustainable energy across Europe, acting as an autonomous body within the European Institute of Innovation and Technology (EIT). Currently EIT InnoEnergy is in the process of setting up the 'European solar initiative'. This is an innovation community bringing together many of the key players in the solar panel value chain in Europe, from mining to recycling, with the shared goal to build a strong and competitive European solar panel industry. InnoEnergy's main role in the European Solar Initiative is to do research, provide background information, define key questions and provide recommendations. Furthermore, they act as an ecosystem builder by bringing together key stakeholders along the entire value chain.

Finding a research topic

InnoEnergy was interested in a thesis collaboration regarding the PV value chain, specifically with a focus on costs and opportunities for lowering these costs. Within this broad domain I conducted a literature review. Based on existing research gaps I decided to focus on the economic potential of the PV recycling industry. This research project contributes to the European Solar Initiative by providing new insights into PV waste streams, their value, future recycling costs and potential profitability of the European PV recycling industry.

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List of abbreviations

BAU :	Business-as-usual
BOS :	Balance of Systems
CMV :	Current Material Value
c-Si :	Crystalline Silicon
EoL :	End of Life
EVA :	Ethylene-vinyl Acetate
FRELP :	Full Recovery End of Life Photovoltaic
IEA :	International Energy Agency
IRENA :	International Renewable Energy Agency
MG :	Moderate Growth
PV :	Photovoltaic
PVC :	Polyvinyl Chloride
PVF :	Polyvinyl Fluoride
R&D :	Research and Development
SG :	Strong Growth
WEEE :	Waste Electrical and Electronomic Equipment

List of symbols and variables

β:	Shape parameter
C_1 :	Current PV recycling costs [€]
C_2 :	Expected future PV recycling costs [€]
$C_{t\ a}$:	Average cost of transport from a PV plant to a collection point [€/t]
$C_{t\ b}$:	Average cost of transport from a collection point to a (FRELP) recycling facility in a given year [€/t]
C_{tot} :	Total recycling costs [€/t]
C_d :	Average cost of disassembling in a given year [€/t]
C_{d1} :	Current disassembling costs (2021) [€]
C_{d2} :	Expected future disassembling costs in a given year [€]
C_{dis} :	Cost per tonne per kilometre [€/(t·km)]
C_p :	Average FRELP recycling process cost in a given year [€/t]
C_{p1} :	Current process costs [€]
C_{p2} :	Expected future process costs in a given year [€]
$C_{t\ WOT}$:	Average cost of transportation without pre-treatment in a given year [€/t]
$C_{t\ WT}$:	Average cost of transportation with pre-treatment in a given year [€/t]
$c_{add}(t)$:	Added PV capacity over year t [MW] (exponential)
$c_{add'00\text{-}'20}$:	Added PV capacity from 2000 to 2020 [MW]
$c_{add'21\text{-}'49}$:	Added PV capacity from 2021 to 2049 [MW]
$c_{dec'00\text{-}'20}$:	Decommissioned PV capacity from 2000 to 2020 [MW]
$c_{dec'00\text{-}'49}$:	Decommissioned PV capacity from 2000 to 2049 [MW]
$c_{dec'21\text{-}'49}$:	Decommissioned PV capacity from 2021 to 2049 [MW]
$c_{ins}(t)$:	Total installed capacity in the beginning of year t [MW]
$c_{ins'21}(t)$:	Total installed capacity in 2021 (at the beginning of the year) [MW]
$c_{ins'50}$:	Total installed PV capacity in 2050 (at the beginning of the year) [MW]
D :	Total electricity demand in 2050 [MWh]

$\mathbf{d}$: Average distance from a PV plant in to a (FRELP) recycling facility in a given year [km]

$\mathbf{d_b}$: Average distance from a collection point to a (FRELP) recycling facility in a given year [km] *('d_b' in the scenario with pre-treatment is the same as 'd' in the scenario without pre-treatment)*

$\mathbf{d_{DE}}$: Rough estimation of the average distance of all PV plants in Germany to the first FRELP recycling facility located in the middle of the country [km]

$\mathbf{d_{EU}}$: Rough estimation of the average distance of all PV plants in the remaining EU member states to the first FRELP recycling facility located in Germany [km]

$\mathbf{d_{F=1}}$: Rough estimation of the average distance of all PV plants in Europe to the first FRELP recycling facility [km]. If F = 1, d = $d_{F=1}$

$\mathbf{F(t)}$: Number of recycling facilities in a given year

$\mathbf{f}$: Capacity factor

$\mathbf{h}$: Total hours in a year [h]

$\mathbf{i}$: Is an integer that represents the steps for the reduction of the average distance by half every time the amount of new facilities is multiplied by a factor 4

$\mathbf{K}$: PV waste collection rate [%]

$\mathbf{k}$: t - 2020

$\mathbf{l}$: Lifetime in years [y], l=0 at the year of installation

$\mathbf{M_{add\ c\text{-}Si}(t)}$: Added c-Si capacity in mass, in year t [kt]

$\mathbf{M_{dec}\ (t)}$: The mass of decommissioned panels in a given year (t) [kt]

$\mathbf{M_{dec\ '21\text{-}'50}}$: The cumulative amount of decommissioned panels from 2021 to 2050 [kt]

$\mathbf{M_f}$: Fraction of the remaining waste

$\mathbf{M_{ins\ y}}$: The installed capacity in mass installed in year y [kt]

$\mathbf{M_{mat}\ (t)}$: Material mass of the materials that are contained in the PV waste, in a given year [kt]

$\mathbf{M_{mod}}$: Module mass [kg/m^2]

$\mathbf{p(l)}$: Cumulative probability of solar panel failure

$\mathbf{p_a(l)}$: The annual probability of decommissioning in a given year of a PV panels lifetime

$\mathbf{P_{mod}}$: Module nominal power [Wp/m^2]

$\mathbf{Q_1}$:	Current size of the PV recycling market [t]
$\mathbf{Q_2}$:	Estimated future size of the PV recycling market in a given year [t]
$\mathbf{R_g}$:	Growth rate
$\mathbf{S_{c\text{-}Si}\ (t)}$:	Market share of c-Si modules as a percentage of the total PV market in a given year t [%]
$\mathbf{S_e}$:	PV electricity market share in 2050 [%]
$\mathbf{S_{mat}}$:	The mass share of the materials, a percentage of the total PV waste [%]
$\mathbf{S_{PV\ DE}}$:	PV market share of Germany [%]
$\mathbf{S_{PV\ restEU}}$:	PV market share of the remaining EU member states [%]
$\mathbf{s}$:	Size / annual capacity of the FRELP recycling facility [t/y]
τ:	Scale parameter
$\mathbf{V_{mat}}$:	value of the various materials [€/t]
$\mathbf{V_{tot}}$:	Total value of the recovered material of one tonne of PV waste [€/t]
$\mathbf{x}$:	Scaling factor
$\mathbf{Y}$:	Recycling yields of the various materials [%]

1 Introduction

1.1 Context and research problem

As Europe is aiming to reduce greenhouse emissions from energy production, the amount of installed solar power in European member states has been growing rapidly over the last couple of years. The photovoltaic (PV) installed capacity has increased from approximately 130 MW to 140 GW during the present century (Madsen & Hansen, 2019). Solar energy is possibly the renewable technology with the most potential to power our future and will definitely play a significant role in the future energy system of Europe.

However, as with all products, PV modules have a certain lifetime during which they can effectively supply electricity, after which they become End of Life (EoL) products. Due to the great increase in solar power capacity , an enormous number of decommissioned solar modules will soon be added to the PV waste stream (Weckend, Wade, & Heath, 2016).

Although a significant amount of research is focused on increasing panel efficiency and decreasing production costs, only a small fraction of attention is given to the PV EoL phase. This can be seen, for example, in the lack of recycling plants specialized in PV technology around the world (Mahmoudi, Huda, Alavi, Islam, & Behnia, 2019).

PV EoL management, which includes disassembling the plants, collection, transport and recycling of modules, will present a real challenge in the future (Latunussa, Ardente, Blengini, & Mancini, 2016). Without proper EoL management a great amount of waste will not be correctly recycled or reused. In a solar dominant energy future this might even lead to a shortage of rare earth metals, which could hamper further adoption of solar panels (Jones, 2013). In order to reduce the amount of waste created and conserve natural resources, it is important to have a solid recycling plan in place. Besides this, recycling of solar panels can increase economic security by using a domestic source of materials for new solar panel production. Furthermore, reducing the need to harvest new raw materials, can decrease carbon emissions, save energy and perhaps even save costs (Latunussa et al., 2016). This makes the PV EoL phase a particularly socially relevant research topic.

To establish a well-grounded recycling strategy it is important to have a comprehensive understanding of the PV waste streams to be expected in the future. Therefore, forecasts of future decommissioned solar panels and their material composition, are essential. The results can be used in various ways. Firstly, to ensure sufficient capacity of the right type of recycling technology is available in the future. Secondly, to setup an appropriate disposal procedure for hazardous materials. Thirdly to examine economic profitability of recycling (Dominguez and Geyez, 2017 ; Peeters et al., 2017 ; Redlinger et al., 2015). To contribute to a solid European recycling strategy, this thesis forecasts the emerging PV waste streams in Europe and investigates the economic potential of the future PV recycling market.

1.2 Existing body of literature and research gaps

A literature review was conducted to position the thesis in the current body of literature, specify relevant research gaps and formulate our research question. The results are summarized below.

1.2.1 PV waste stream assessments around the world

Although, not many studies on PV waste streams have been conducted, various features of the studies that have been carried out are of interest to shape our research.

As the exact moment when PV panel failure occurs cannot be identified, PV waste stream studies often use a continuous probability distribution to estimate solar panel lifetime and the distribution of solar panel decommissioning (Mahmoudi, Huda, & Behnia, 2019; Santos & Alonso-García, 2018; Peeters, Altamirano, Dewulf, & Duflou, 2017).

A majority of the studies focus on the amount of expected recovered materials instead of the economic value of this material, neglecting the economic dimension of the issue (Domínguez & Geyer, 2017, 2019; Paiano, 2015; Santos & Alonso-García, 2018). Some authors do calculate the economic value of recovered materials, however they base this on current commodity prices (Mahmoudi, Huda, & Behnia, 2019; Monier & Hestin, 2011). Peeters et al. (2017), is the only study found, that look into possible fluctuation of material value in the future. Although it is interesting to estimate the value of the recovered materials, they do not compare it to the expected costs of recycling. Therefore, they cannot conclude anything regarding a possible profit for recycling of this material. This information would be of great interest for policymakers or entrepreneurs that consider entering the recycling industry in the future.

Monier and Hestin (2011) is the only waste stream study that was found that investigates the European Union (EU) as a whole. However, this study is 10 years old and currently there is more data available on newly added solar PV capacity. Looking at the existing literature, no waste stream forecast has been executed for Europe since. This makes it valuable to carry out a current and therefore, more accurate waste stream assessment for Europe. Monier and Hestin (2011), also seems to be the single waste stream forecast study that took recycling costs into account. However, they used recycling prices of 2011, completely disregarding possible changes in future recycling costs over the years.

1.2.2 PV recycling costs

In general, only a small fraction of the PV recycling literature investigated costs of recycling. Most studies that do, agree that at the moment there is often no profit to be made with the recycling of PV modules (McDonald & Pearce, 2010; Redlinger, Eggert, & Woodhouse, 2015). Due to the relatively small amount of solar PV waste, recycling seems to be more expensive than the value of the recovered material (Redlinger et al., 2015).

Learning and economies of scale can potentially reduce recycling costs significantly (Redlinger et al., 2015). However, a substantial amount of PV waste is necessary to make recycling viable and economically feasible (Mahmoudi, Huda, Alavi, et al., 2019). Redlinger et al.

(2015) state that future research should focus on providing better estimates of recycling costs in future scenarios. Since recycling costs are expected to decrease with the increasing scale of the recycling market, one needs to have a good idea of the expected total volume of PV waste in order to estimate future recycling costs. This makes it especially interesting to combine a waste stream study with an economic potential forecast.

1.3 Main research question

In order to contribute to the current body of literature this thesis will conduct a PV waste streams forecast for Europe up until 2050. The PV waste forecast will be done for multiple future installed PV capacity scenarios and the decommissioning is assessed using a continues probability distribution. Furthermore, the potential profitability of PV recycling in future scenarios is examined, taking into account economies of scale using a scaling function and possible fluctuation of material prices. To the best of our understanding, this study is the first to apply a scaling law to analyse the future economic potential of the PV recycling market. Lastly, based on the results, suggestions for future PV EoL management are made.

This thesis aims to answer the following main research question:

> "What is the economic potential of the PV recycling industry in Europe up until 2050, based on expected waste streams?"

1.4 Thesis outline

The thesis proceeds as follows:

- In **chapter 2**, the research approach and methodology is discussed. This chapter provides insights into how the research is conducted.
- **Chapter 3**, consists of a literature review, in which key aspects of the current PV market and EoL management in Europe are illustrated. This information is used to design a waste stream forecast model.
- **Chapter 4** provides a comprehensive explanation of the model conceptualization. In this chapter all additional data sources are introduced. Furthermore, validation of the model and the sensitivity analysis are discussed.
- In **chapter 5**, future PV waste volumes are analysed, providing the annual and cumulative expected material streams.
- **Chapter 6** investigates the economic potential of the future PV recycling industry. This chapter provides information on expected material value and various types of costs related to PV recycling.
- **Chapter 7** consists of a discussion of the results. In this chapter the results are positioned in the current body of literature, a reflection on the methods is provided and based on the main limitations of this study, future research suggestions are made.
- **Chapter 8** consists of a conclusion, providing an answer to the the main research question.
- Lastly, **chapter 9** reflects on the results and provides some recommendations for future PV EoL management in Europe.

2 Research approach and methodology

In this chapter the research approach and methodology will be discussed. The objective this chapter is to provide a solid understanding of how the research is conducted, what aspects are included and how an answer to the main research question is formulated. First, the general research approach and sub-questions are introduced. Second, the analytical framework is discussed, providing further insights in the research approach and research scope. Lastly, the methodology is illustrated.

2.1 Approach and sub-questions

The aim of this research is to estimate the economic potential of the PV recycling market, by conducting a scenario-based forecast. In order to give a comprehensive answer to the main research question the following steps are taken. First, by reviewing relevant literature, the current PV market is discussed and contemporary EoL practices are illustrated. Information gathered during this first step is used to design a waste stream forecast model.

Next, using the model, a forecast of future PV waste streams will be conducted. Based on the waste stream forecast, recovered material value and recycling costs are estimated. By comparing the material value and total recycling costs the economic potential of the PV recycling market is analysed. Finally, based on these findings, some recommendations are made for future PV EoL management in Europe. The analysis will be carried out using the following sub-questions:

1. What aspects of current PV EoL management in Europe are relevant for the forecasting model?
2. What PV waste volumes and material streams can be expected in Europe up until 2050?
3. What is the estimated value of the PV waste stream?
4. What are the estimated future costs of PV recycling?
5. Will PV recycling be profitable in the future?

2.2 Analytical framework

To clarify the scope of the study and how the research problem will be approached, an analytical framework is provided. The research consists of two main steps. step one, is conducting a **waste stream assessment**. Step two, is carrying out an **economic potential assessment**, based on the results of the waste stream assessment. The key concepts, 'PV waste streams' and 'economic potential', are specified below. Furthermore, corresponding parameters and variables are discussed. The framework is illustrated in figure 2.

2.2.1 PV waste streams

In this study PV waste streams are defined as the volume of PV modules (in weight) that have reached the end of their life and are decommissioned. The waste streams contain 'material' streams, which are defined as the amount of individual materials (e.g. aluminium, glass, silver, silicon, copper and plastic) that are contained in the PV waste.

The yearly European PV waste and material streams up until 2050 will be examined. The estimations are based on total historic installed PV capacity (2000-2020) and multiple future installed capacity scenarios (2021-2049). Future added capacity is important to take into account, as it can be expected that a significant part of waste volumes up until 2050 will consist of PV modules that are currently not installed yet.

This research focuses solely on the PV modules itself. The junction box and the Balance of Systems (BOS) such as wiring, batteries, inverters and the mounting system, are not taken into account, as these require a totally different recycling process.

Furthermore, as over 90 percent of all the installed solar panels are made from silicon (c-Si) (Domínguez & Geyer, 2017), and a more accurate economic potential assessment can be done while focusing on one technology, only c-Si panels will be considered in this research. c-Si panels typically exist out of a glass shield, aluminium frame and 'PV sandwich'. The PV sandwich exists out of silicon solar cells, containing various metals such as silver, copper, tin and lead, and a polymer plastic backsheet (Markert, Celik, & Apul, 2020). To estimate the material streams, information on average PV module material composition is necessary.

Weibull distribution

The Weibull distribution is chosen to forecast PV decommissioning, since it has proven to be one of the most effective tools to predict PV module failures over time and the necessary parameter values are readily available (Domínguez & Geyer, 2019; Espinet-González et al., 2013; Santos & Alonso-García, 2018; TamizhMani & Kuitche, 2013). The Weibull distribution is a continues probability distribution, widely used in reliability research and lifetime data analysis to forecast system failures (Das, 2008). Based on existing data sets, the probability of system failure in a given year is determined. Subsequently this data is used as input for the Weibull parameters. This provides a statistical distribution, which can then be used to predict annual system failure (see example in figure 1).

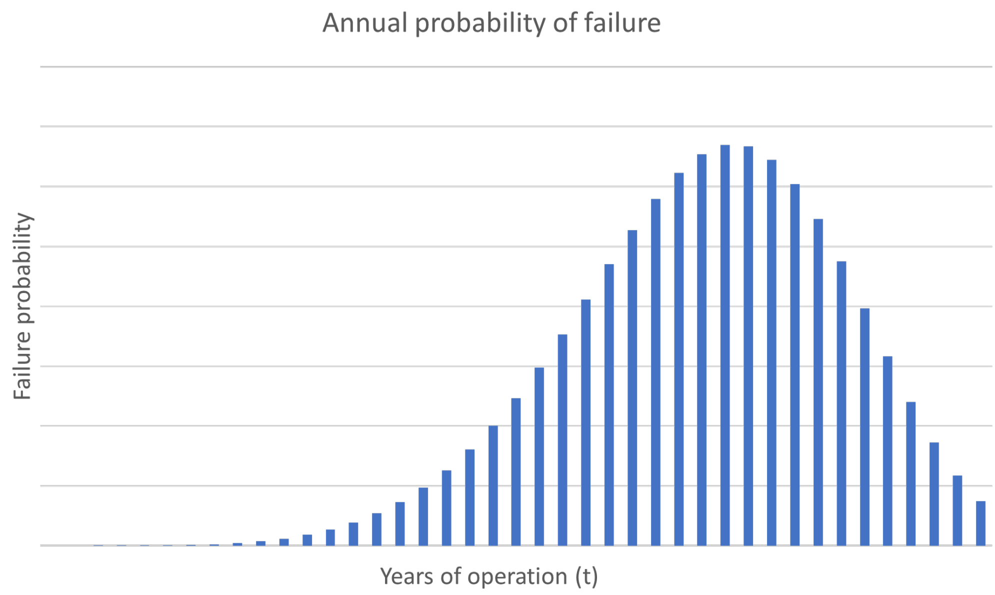


Figure 1: Example of a weibull distribution

The input data necessary to do the waste stream assessment is summarized below:

- Annual added PV capacity per member state
- Annual c-Si market share
- Average PV module specifications (weight and nominal power)
- Average material composition of the PV modules
- Weibull parameters representative for PV module failure

Using the data described above, a waste and material stream forecast is carried out (For a detailed explanation see chapter 4). The results are used as input for the **economic potential assessment**, to estimate future material value and recycling costs.

2.2.2 Economic Potential

In this study an economic potential is defined as the potential of creating a surplus of value in the PV recycling market. The economic potential is based on 'recovered material value' and estimated 'total recycling costs'. In order to create a surplus, total value should exceed total costs.

The **recovered material value** is based on the results of the waste stream assessment, average recycling yields and material prices. To be able to compare two possible future realities, two recycling yield scenarios will be investigated, one based on a 'baseline scenario' and one based on the 'FRELP recycling process', which will be further discussed in chapter 3 and 4. Furthermore, the material price depends on the purity of the recycled material and on fluctuations in commodity prices (see chapter 4).

The variables necessary to calculate recovered material value are summarized below:

- The waste volume (result of waste stream assessment)
- Material composition (determined in waste stream assessment)
- Average recycling yields
- Material prices

The **total recycling costs** cover all expenses from the moment modules are decommissioned up until recycling. As information regarding externality costs (e.g. carbon emissions and other pollutants) of dismantling and recycling is currently lacking, externalities are not taken into account in the model calculations. Although not part of the model, the main externalities are briefly discussed in chapter 9.

The costs are divided into three categories:

- Disassembling costs
- Transportation costs
- Recycling process costs

The cost categories will be further discussed in chapter 3 and 4.

Economies of scale

To analyse cost reduction as a result of the increasing PV recycling market size, future disassembling and recycling costs will be investigated based on the notion of economies of scale. Economies of scale are cost advantages due to an increase in output volume. A distinction can be made between internal and external economies of scale. Internal economies of scale are company-specific, are rooted internally and occur regardless of the industry. External economies of scale are caused by the growth of the industry in general and affect all firms operating in the industry at hand. Growth of the industry may allow access to more specialist suppliers, lower-cost equipment, improved technology, or a more skilled workforce (Kenton, 2021). This research focuses on external economies of scale, as it looks at Europe's PV recycling market in general.

External diseconomies of scale on the other hand, happen when markets mature and reach a certain magnitude, potentially causing scarcity of specialized labor, natural resources or infrastructural capacity (Gelles & Mitchell, 1996). Although, in the more distant future, diseconomies of scale might also play a role in the PV recycling market, as the industry is currently still in the infancy-phase, diseconomies of scale are not likely to happen in the coming years. Therefore, they are not incorporated in this research.

In economics and engineering, scaling laws are used to make sense of the effects of economies of scale. Scaling laws describe the size relationship between two variables that scale over a certain time interval. In this research the two variables are 'market size' and 'recycling costs'. If current costs, current market size and future market size are known, based on a scaling factor future costs can be estimated. The application of economies of scale in the forecasting model is further explained in chapter 4.

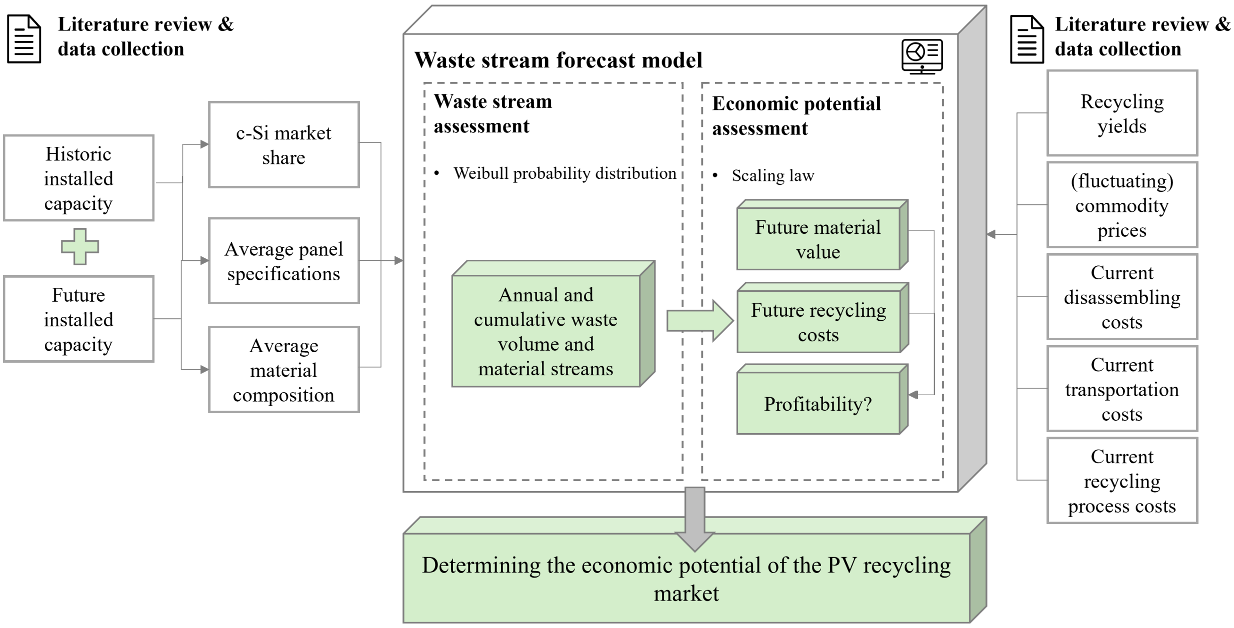


Figure 2: Analytical framework

2.2.3 Expectations based on existing literature

Based on the literature, large waste streams are expected starting from the year 2030-2035 (Domínguez & Geyer, 2017; Mahmoudi, Huda, Alavi, et al., 2019). As long as waste volumes are insignificant, no real profit is expected to be made in the PV recycling market (McDonald & Pearce, 2010; Redlinger et al., 2015). Opinions are divided regarding the profitability of the future PV recycling market. Most studies agree that there is significant material value in the emerging PV waste streams (Mahmoudi, Huda, & Behnia, 2019; Peeters et al., 2017), but as PV recycling is a rather difficult and expensive task, no real consensus is reached on whether the waste streams can actually be capitalized on.

2.3 Methodology

In this section the research methodology is briefly discussed, providing insights into how data is gathered and results are constructed in this study. To conduct the forecast, first a literature review was carried out. Second a scenario-based forecast model was built in python.

2.3.1 Exploration

To answer sub-question 1, a literature review of the current PV EoL management situation in Europe was conducted (chapter 3). The aim of this literature review was to find information that could be used as input to design the model. Based on the current PV EoL management situation, scenarios were developed and modelling choices were made. The actual conceptualization of the model can be found in chapter 4.

2.3.2 Scenario-based forecast modelling

The aim of scenario-based forecasting is to predict what is likely to happen in future years based on a range of plausible scenarios (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). Forecasts can indicate potential challenges in certain scenarios, enabling policy makers to design policy solutions accordingly. Furthermore, they can assist investors and entrepreneurs in taking advantage of potential opportunities (Börjeson et al., 2006).

PV waste stream forecast model

To estimate waste streams (sub-question two), future value of recovered material (sub-question three), costs of recycling (sub-question four) and the profitability of the market (sub-question five), a 'PV waste stream forecast model' was built in Python. A modelling approach was used in this study as it enabled us to to simplify a real world system, providing an opportunity to test various scenario's. Python was chosen as a modeling tool, as it is capable of handling large data sets and, is effective at data analysis and visualisation.

A quantitative forecasting model can be used to predict the value of future variables, based on historic data, current data and by analysis of future trends. The **variables** investigated in this research are future PV waste volumes, future material streams, future material prices and future recycling costs. Predictions concerning these variables have been done based on historic installed PV capacity, expected future installed PV capacity, average material composition, current material prices and current recycling costs (see section 2.2 for how they relate to each other and section 4 for how they are applied). The two main **future trends** examined in the model are the solar power decommissioning pattern and the changing recycling costs over the years. The solar panel decommissioning pattern is projected based on a Weibull distribution, while future recycling costs were estimated based on the notion of economies of scale, using a scaling law (see section 2.2).

All data necessary as input for the model, was collected based on an extensive literature study and information gathered from industry experts. In chapter 4, a detailed explanation of the waste stream forecast model is given, elaborating on the scenarios, input data, functions, assumptions and variables that together construct the model.

3 Current PV EoL management in Europe

In this chapter, based on a literature review, the aspects of current PV EoL management in Europe that are most relevant for constructing the model, are discussed. A solid understanding of the current situation in Europe is a requisite to make key modelling decisions and build a PV waste stream forecasting model that represents reality. This chapter provides an answer to the first sub-question:

> **Sub-question 1:** What aspects of current PV EoL management in Europe are relevant for the forecasting model?

First, historic installed PV capacity is discussed. Next, current PV EoL management is analysed, looking into PV recycling legislation, waste collection, transportation and the recycling process.

3.1 Historic installed PV capacity

Europe is one of the biggest markets for PV technology in the world and has a combined installed capacity of approximately 140 GW (Madsen & Hansen, 2019). Germany is Europe's leading PV industry with an installed PV capacity of 54.6 GW (Madsen & Hansen, 2019). After Germany, the European nations with the most installed capacity are: Italy (21.3 GW), Spain (13.3 GW), France (10.9 GW), the Netherlands (9.2 GW), Belgium (5.4 GW), Poland (3.6 GW) and Greece (3.4 GW) (Madsen & Hansen, 2019). Figure 3 shows the annually added solar PV capacity in Europe from 2000-2020.

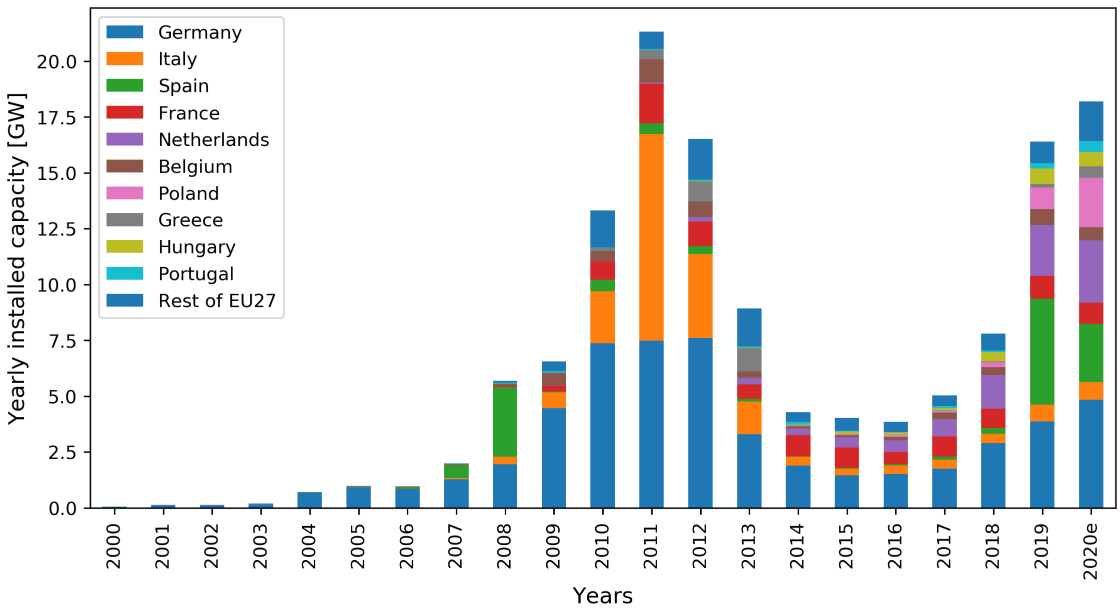


Figure 3: Annually added PV capacity 2000-2020, based on data from SolarPowerEurope (2020).

Model implication

The data on total PV capacity in Europe described above, will be used in the model to predict future waste streams. Future installed PV capacity scenarios will be added to the data set, these will be discussed in chapter 4. The added capacity before 2000 is negligible and will therefore not be included in the model.

3.2 PV recycling legislation

To understand the financing of PV EoL management, it is important to be aware of the EU PV recycling legislation. Europe is the first continent in which solar panel producers are now responsible for the EoL management of their products (Chowdhury et al., 2020). In 2014, solar panels have been added to the Waste Electrical and Electronic Equipment (WEEE) directive (Weimar, 2012). Producers are now obliged to collect and recycle waste panels in each member state.

There are two main issues with the WEEE directive, related to the financing of PV EoL management. First, Solar panels have a rather long lifetime, approximately 25-30 years. The long lifetime presents recycling responsibility issues, since PV producers are potentially already out of business when their product reaches the end of its lifetime (Fthenakis, Eberspacher, & Moskowitz, 1996). This results in lower collection rates and hinders PV recycling. As a solution, in some European member states, such as France and Belgium, the costs of recycling are paid in advance. However, currently such a payment scheme is only implemented in a minority of the EU member states.

Second, these fees only cover the costs of transportation and recycling, excluding the costs of disassembling of the modules. As this is not covered in the WEEE directive, it remains unclear who is responsible for the costs incurred during disassembling. This legal unclarity potentially causes non-functioning PV plants to remain on-site for years, as a result of insufficient responsibility and monetary means for disassembling (Franz & Piringer, 2020).

Model implication

Fees are primarily necessary to ensure disassembling, transportation and recycling, as long as EoL management is more expensive than the value of the recovered material. If recycling is profitable, producers have an incentive to recycle. Therefore, to investigate if pre-paid fees will be needed in the future, the forecast model used in this study will look at economic potential based on the notion that all costs (disassembling, transportation and recycling) incurred during the PV EoL phase, have to be covered by the recovered material value. In a scenario of a negative business case, the WEEE directive will need to be adapted to also guarantee the disassembling of future EoL modules.

3.3 Waste collection

Although the EU aims to collect 85 percent of the decommissioned PV modules, based on PV sales and waste-collection data, currently only 47 percent of the PV waste is collected (EC, 2018; Franz & Piringer, 2020). Even though there is recycling legislation in place in Europe, decommissioned panels do not always end up in recycling facilities. When solar panels are decommissioned in Europe they are either processed in a recycling plant, end up in landfills or get a second life in a developing country (Franz & Piringer, 2020; Okoroigwe, Okoroigwe, Ajayi, Agbo, & Chukwuma, 2020).

Model implication

To investigate if the PV recycling market has economic potential in case the waste collection targets of the EU are achieved, an 85 percent collection rate is used in the model.

3.4 Transportation

When PV panels are recycled, the decommissioned panels are first shipped to the nearest central collection point (Choi & Fthenakis, 2010). A central planning agency and waste management organization such as 'PV CYCLE' will provide recycling containers which are used to store the old panels. When the containers are full, the PV waste is transported to a designated recycling facility.

Although collection points might be effective to cluster small scale consumer PV waste, they are often inefficient for large scale waste, as no cost efficiency is gained by clustering large scale waste at collection points. (Choi & Fthenakis, 2010). In case collection points notably increase the total distance, sometimes it is actually significantly more cost effective to directly transport the PV waste to a recycling plant (Choi & Fthenakis, 2010). On the other hand, collection points could be used for waste pre-treatment, decreasing the total weight that has to be transported to the recycling facility (Ardente, Latunussa, & Blengini, 2019), potentially decreasing costs and carbon emissions.

Model implication

To see if there might still be a place for the collection points in future EoL management, in the model two transportation scenarios are investigated. I) Transportation without pre-treatment, in which collection points are skipped and waste is directly transported to the recycling plant. II) Transportation with pre-treatment, in which collection points are used for the first step of the FRELP recycling process. FRELP is further explained below.

3.5 Recycling process

Currently, PV waste is often still treated in general purpose recycling plants. In these facilities only the aluminium and some of the glass is recovered, neglecting to retrieve some of the more valuable materials found in PV waste (Mahmoudi, Huda, Alavi, et al., 2019). Due to relatively low quantities of PV waste, recycling the other materials is not economical. According to Luo (2021), the remainder of the materials (silver, silicon, copper and more) is grinded down for incineration to generate energy in cement ovens.

Various c-Si recycling methods are proposed, ranging from simplistic mechanical recycling, with low recycling yields, to more complex methods such as thermal treatment or chemical edging (Lunardi, Alvarez-Gaitan, Bilbao, & Corkish, 2018; Xu, Li, Tan, Peters, & Yang, 2018). The main issue with most proposed methods is that they only focus on extracting a couple of materials and do not offer a solution for all necessary material extraction material steps.

3.5.1 The Full Recovery End of Life Photovoltaic project (FRELP)

One of the most promising PV recycling projects is the Full Recovery End of Life Photovoltaic project (FRELP) (Faircloth, Wagner, Woodward, Rakkwamsuk, & Gheewala, 2019; Heath et al., 2020; Latunussa et al., 2016; Markert et al., 2020). The FRELP approach differs from other recycling methods, as it offers a technical solution that is able to extract all valuable materials (Markert et al., 2020). FRELP is considered current 'best practice', as it has shown one of the highest PV recycling yields in laboratory tests (Heath et al., 2020; Latunussa et al., 2016). This combined with 'relatively' low costs, gives it the potential to be utilized on a commercial scale (Heath et al., 2020; Latunussa et al., 2016).

This makes it especially interesting to test future potential profitability based on the specifications of this specific technology. Therefore, data on the FRELP process will be used in the model to investigate the economic potential of the PV recycling market.

The FRELP process can be divided into three material extraction steps (see figure 4) (Sasil, 2015). In **step one**, the junction box and aluminium frame are mechanically removed from the panel. Next, the glass shield is removed by use of infrared heating (Latunussa et al., 2016). About 94.4 percent of aluminium and 98 percent of the glass is recovered (Heath et al., 2020). The junction box is sent to another facility for further treatment and is not included in this study. As step one is relatively uncomplicated it can potentially be executed at collection points as pre-treatment (Ardente et al., 2019). This possibility will be further discussed in chapter 4.

In **step two**, the silicon material is extracted from the PV sandwich. First, the remaining PV sandwich is incinerated (Sasil, 2015). The ash residue, containing the remaining metals, is put through a leaching process recovering about 97 percent of silicon in the form of silicon metal at metallurgical grade (Heath et al., 2020; Latunussa et al., 2016) .

In **step three**, by use of electrolysis, silver and the remaining copper are extracted from the residual material, with an efficiency of approximately 94 and 97 percent, respectively (Heath et al., 2020; Sasil, 2015). The residue (containing tin and lead) is eventually disposed in special landfills that ensure the toxic waste does not leak into the ground and contaminate groundwater (Latunussa et al., 2016).

The material scraps (e.g. glass, aluminium, copper, silver and silicon) are sold to metal refineries that are specialized in further processing of the materials (Latunussa et al., 2016). According to Ramon (2021), for the FRELP process to be commercially interesting, it needs to process approximately 20 kt of waste per year. However, currently there is not enough waste to run a FRELP facility at full capacity.

Model implication

The application in the model is two fold. First, the economic value of the waste stream is calculated based on recycling yields of both, current recycling practices and the more advanced FRELP process. Comparing the scenarios, illustrates the material value that could be gained by changing current recycling processes to a more advanced process, with higher recycling yields, like FRELP.

Second, data on FRELP recycling yields and recycling costs will be used in the model to examine the economic potential of the PV market. As FRELP is considered 'best practice', if there is no business case for FRELP, it is unlikely that there currently is another recycling method for which this is the case.

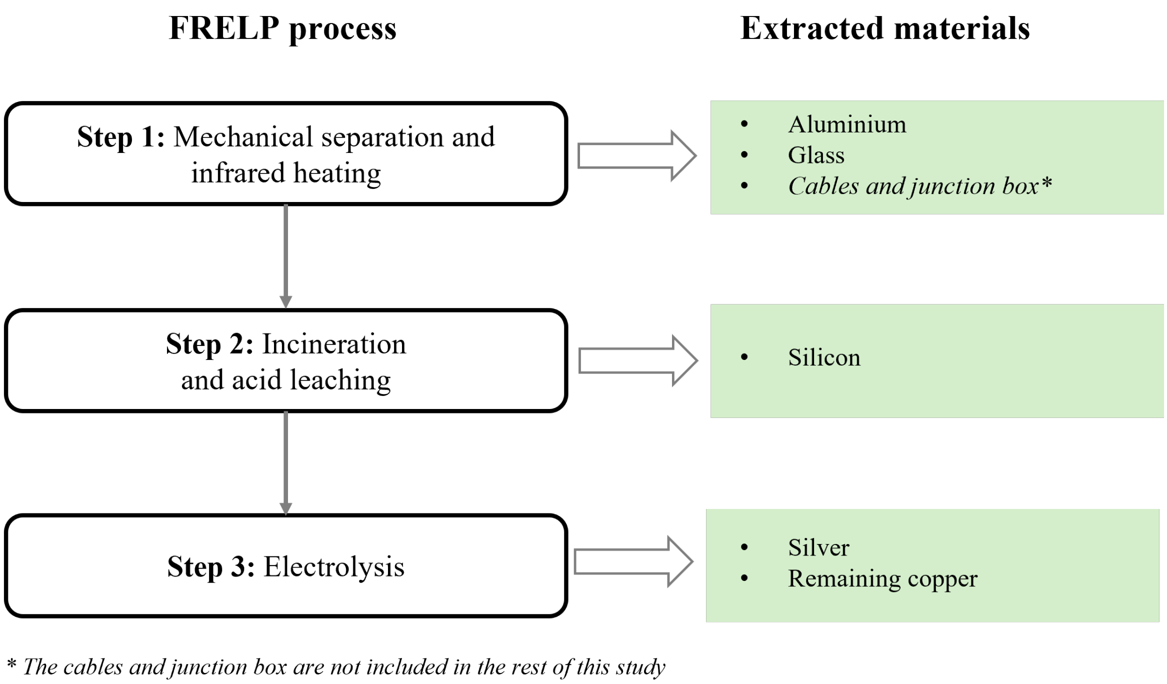


Figure 4: FRELP recycling process steps.

3.6 Sub-question 1: Current PV EoL management

In this section the current PV market and PV EoL practices in Europe were analysed, to find information to design the PV waste stream forecast model. This provided an answer to the following sub-question:

> *What aspects of current PV EoL management in Europe are relevant for the PV waste stream forecasting model?*

- The annually added PV capacity in Europe from 2000-2020 is necessary to model future waste streams.
- To figure out if (pre-paid) fees will be necessary in the future to ensure recycling, the model used in this study investigates economic potential of the PV recycling market based on the notion that all costs (disassembling, transportation and recycling), have to be covered by the recovered material value.
- The EU aims to collect 85 percent of PV waste. To investigate if there is an economic potential in the market if these targets are achieved, an collection rate of 85 percent is assumed in the model.
- Currently collection points are used to cluster PV waste before it is transported to a recycling facility. Opinions vary on the effectiveness of the use of collection points. Therefore, to figure out if collection points should play a role in future PV EoL management in Europe, a transportation scenario with and without collection points will be investigated in the model.
- The FRELP recycling process is considered to be current best practice. Therefore, data on the FRELP process (recycling yields and costs) will be used in the model to investigate the economic potential of the market.

4 Model conceptualization

In this chapter the PV waste stream forecast model and corresponding variables, assumptions and modelling choices are elaborated upon. Additionally, the data sources, model validation and results of the sensitivity analysis will be discussed.

The PV waste stream forecast model consists of two parts: First, a **waste stream assessment** is carried out to get a better understanding of the waste volume and material streams that can be expected. Second, an **economic potential assessment** is executed, estimating the current and possible future value of the PV waste, and the expected costs of recycling. Based on the material value and recycling cost estimates, the economic potential of the market is analysed.

4.1 Waste stream assessment

To predict waste streams up until 2050, first the total historic and expected future installed capacity is determined. Second, the PV capacity in megawatt is converted to PV capacity in weight. Third, based on the probability of module failure, the decommissioning pattern is decided upon. Finally, based on average material composition data, material flows are estimated.

> Note:
>
> A distinction is made between 'added' capacity and 'installed' PV capacity. *Added capacity* is the PV capacity added to the total capacity in a certain time frame. *Installed capacity* is the total PV capacity installed at a certain moment in time.

4.1.1 Historic installed capacity

The 10 biggest solar markets in Europe are investigated individually, while installed capacity of the remaining countries are added together (Rest of EU27). Figure 3 provides an overview of the historically added annual PV capacity in Europe from 2000-2020. Figure 5, illustrates the cumulative PV capacity in Europe from 2000-2020, based on data from SolarPowerEurope (2020).

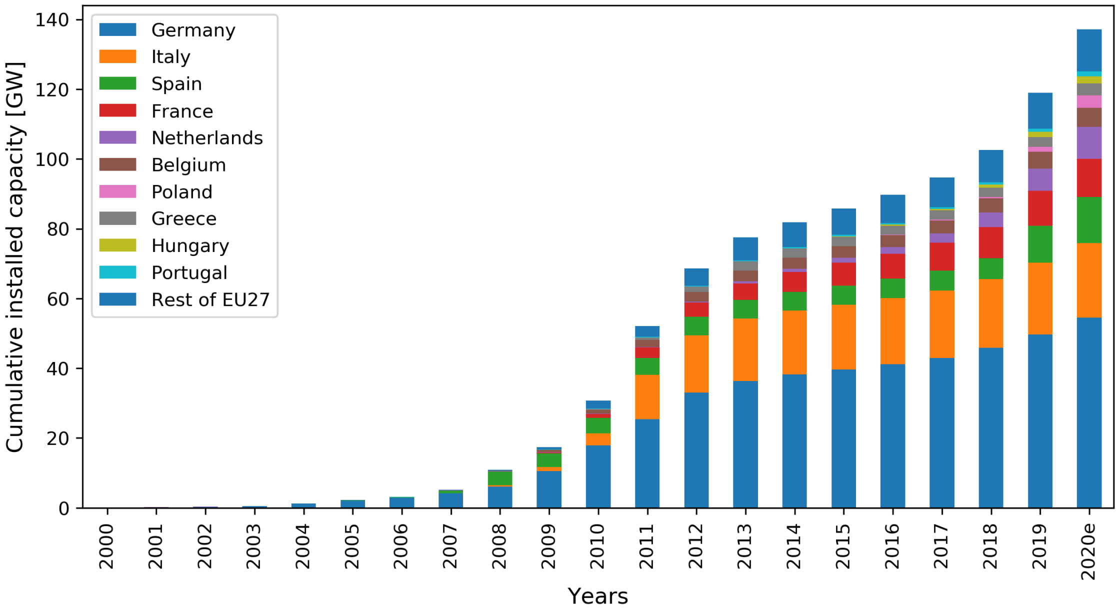


Figure 5: Cumulative PV capacity in Europe 2000-2020, based on data from SolarPowerEurope (2020).

4.1.2 Future installed capacity

To allow us to investigate various potential future realities, the expected future installed capacity will be estimated based on three scenarios. A business-as-usual, moderate growth and strong growth scenario will be examined.

Business-as-usual scenario

The business-as-usual scenario assumes that solar power will play a modest role in the energy system of the future. Although the total installed capacity will grow relative to 2021, The PV market share in 2050 in the this scenario is estimated to be similar to what it is in 2021, which is approximately 5 percent of the total electricity demand.

Moderate growth scenario

In the moderate growth scenario, the market share of solar energy will grow steadily. Although other energy technologies have a greater market share, solar energy will still have a significant contribution to the electricity supply. For the moderate growth scenario, installed PV capacity is based on a 25 percent electricity market share of PV technology.

Strong growth scenario

The strong growth scenario looks at yearly installed solar capacity based on the notion that solar power is to be the dominant energy source in a carbon zero future. For this scenario it is assumed that 50 percent of all electricity in 2050 will be solar power.

Annually added future PV capacity

To calculate the annually added future PV capacity, first the total installed PV capacity in 2050 is determined. Next, based on historic installed capacity and expected decommissioning, the extra PV capacity that needs to be added between 2021-2049 to reach the necessary installed capacity in 2050, is calculated. Last, the annually added future PV capacity is determined based on a linear or exponential growth, depending on the scenario.

Total installed PV capacity in 2050

First, the installed PV capacity necessary to supply a certain percentage of the total electricity demand in 2050 is calculated. The total electricity demand in Europe in 2050 is based on the average of two forecasts carried out by the European commission and is estimated to be 4,198 TWh (EC, 2018). To calculate the amount of electricity supplied by solar energy in 2050, the PV market penetration for each scenario is multiplied with the total electricity demand. In order to calculate the installed capacity in 2050 that is necessary to supply this share of the electricity demand, the estimated electricity supplied by solar energy in 2050 is divided by the number of hours in a year (8760 h) and the average PV capacity factor. According to the International Energy Agency (IEA) the average capacity factor in Europe is 0.15 (IEA, 2018). As the spread of PV capacity is not equal throughout Europe and the capacity factor can vary among regions, the actual average capacity factor of all PV installed might slightly differ from the European average. However, the average of the continent is accurate enough for a rough estimation. Equation 1 is used to calculate the total installed PV capacity in 2050 for the various scenarios.

$$c_{\text{ins'50}} = \frac{D}{h \times f} \times \frac{S_{\text{e}}}{100\%} \tag{1}$$

$c_{\text{ins'50}}$: Total installed PV capacity in 2050 (at the beginning of the year) [MW]

D : Total electricity demand in 2050 [MWh]

h : Total hours in a year [h]

f : Capacity factor

S_e : PV electricity market share in 2050 [%]

Total added PV capacity from 2021-2049

To estimate the PV capacity that needs to be added from 2021-2049 for each scenario, the historic PV capacity from 2000-2020 is subtracted from the total expected installed capacity in 2050. Furthermore, a significant number of panels, especially modules installed before 2020, will be decommissioned before 2050. This means that, in order to reach the necessary installed capacity to supply a certain percentage of electricity in the future, the panels that are decommissioned in the meantime need to be replaced. The expected amount of decommissioned panels are added to the installed capacity of 2050 to get the actual amount of panels that need to be added from 2021-2049, to reach a certain PV market share in 2050 (equation 2).

$$c_{\text{add'21-'49}} = c_{\text{ins'50}} - c_{\text{add'00-'20}} + c_{\text{dec'00-'49}} \tag{2}$$

$c_{\text{add'21-'49}}$: Added PV capacity from 2021 to 2049 [MW]

$c_{\text{add'00-'20}}$: Added PV capacity from 2000 to 2020 [MW]

$c_{\text{dec'00-'49}}$: Decommissioned PV capacity from 2000 to 2049 [MW]

Annually added PV capacity from 2021-2049

The annual growth of installed capacity is assumed to be linear in the model for the business-as-usual scenario, as the growth of new PV capacity is modest, while an exponential growth is assumed in the other two scenarios. To estimate the annually added capacity for the business-as-usual scenario from 2021-2049, the calculated total added capacity from 2021-2049 is simply divided by 29 years. For the other two scenarios the annually added PV capacity is based on an exponential function, shown in equation 4. The growth rate depends on the difference between the total installed capacity in the beginning of 2021 (equation 3) and the expected total installed capacity in beginning of 2050 (equation 1), which differs per scenario. The growth rate is calculated using equation 5. The actual added annual PV capacity will somewhat fluctuate over the years from 2021-2049. However, the methods described above give a good prediction of annually add future capacity, to calculate future PV waste streams.

$$c_{\text{ins'21}} = c_{\text{add'00-'20}} - c_{\text{dec'00-'20}} \tag{3}$$

$c_{\text{ins'21}}$: Total installed capacity in 2021 (at the beginning of the year) [MW]

$c_{\text{dec'00-'20}}$: Decommissioned PV capacity from 2000 to 2020 [MW]

$$c_{\text{add}}(t) = c_{\text{ins'21}} \times (1 + R_{\text{g}})^k - c_{\text{ins}}(t) \tag{4}$$

$c_{\text{add}}(t)$: Added PV capacity over year t [MW] (exponential)

R_{g} : Growth rate

$c_{\text{ins}}(t)$: Total installed capacity in the beginning of year t [MW]

k = t - 2020

$$R_{\text{g}} = \left(\frac{c_{\text{ins'50}} + c_{\text{dec'21-'49}}}{c_{\text{ins'21}}} \right)^{\frac{1}{29}} - 1 \tag{5}$$

$c_{\text{dec'21-'49}}$: Decommissioned PV capacity from 2021 to 2049 [MW]

Based on the equations described above, the annually added capacity from 2021-2049 is calculated for each scenario. The historic PV capacity from 2000-2020 added to each of the future PV capacity scenarios, provides the annually added capacity from 2000-2049. This data set forms the basis of the waste stream assessment. Figure 6 illustrates the cumulative growth of installed PV capacity, in Europe, for all three scenarios.

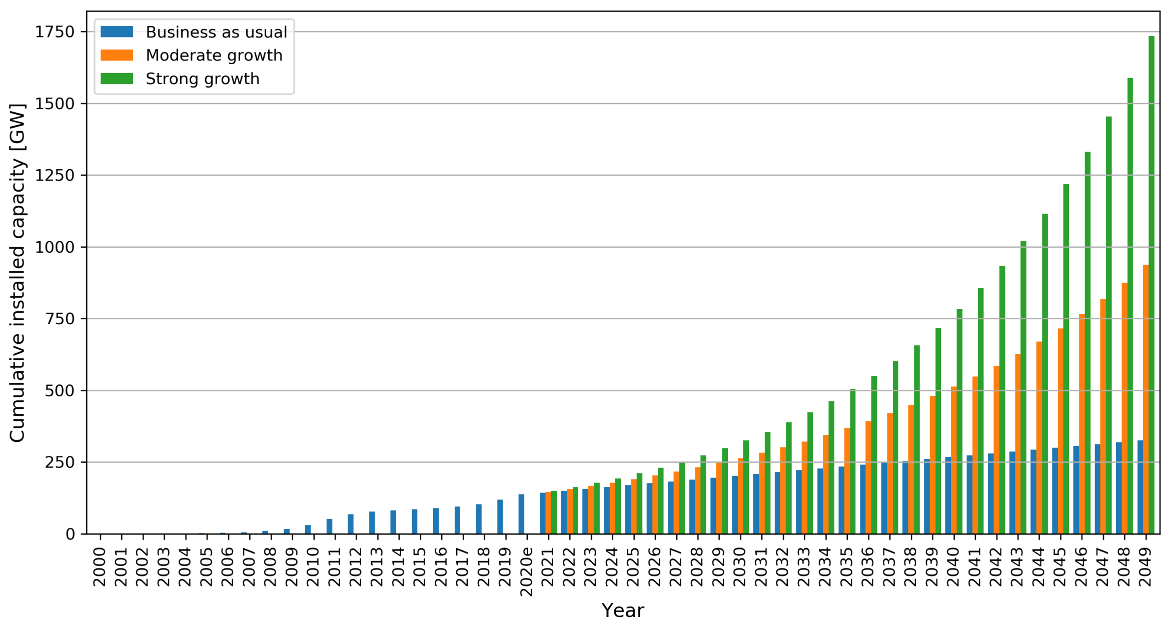


Figure 6: Cumulative growth of PV capacity in Europe for the three scenarios.

4.1.3 c-Si installed capacity

As described in chapter 2.2, this project focuses on waste streams of c-Si panels only. Therefore, in order to estimate the annually added silicon PV capacity, the historic and expected future market share of silicon modules is multiplied with the annually added PV capacity. The market share of silicon PV is based on global averages and future predictions (see table 1) (Monier & Hestin, 2011; Weckend et al., 2016; Domínguez & Geyer, 2017).

Table 1: Market share of silicon panels of the total PV market.

Year	Market share c-Si PV [%]
2000 - 2004	90
2005 - 2009	95
2010 - 2014	80
2014 - 2020	91
2021 - 2050	90

4.1.4 Installed capacity: from power to weight

To investigate future waste volumes and eventually their material composition, first, PV capacity in megawatt (MW) is converted to PV capacity in weight (metric tonnes). This is based on the average weight of silicon solar panels for a certain amount of PV capacity. According to Domínguez and Geyer (2017), the average weight and nominal power per square meter for c-Si solar panels are 15.75 (kg/m^2) and 153 (Wp/m^2) respectively. The annually added PV capacity, annual market share, average weight and average nominal power, are used to compute the metric tonnes of annual added silicon PV capacity (equation 6).

$$M_{\text{add c-Si}}(t) = \frac{c_{\text{add}}(t) \times M_{\text{mod}}}{P_{\text{mod}}} \times \frac{S_{\text{c-Si}}(t)}{100\%} \tag{6}$$

$M_{\text{add c-Si}}(t)$: Added c-Si capacity in mass, in year t [kt]

M_{mod} : Module mass [kg/m^2]

P_{mod} : Module nominal power [Wp/m^2]

$S_{\text{c-Si}}(t)$: Market share of c-Si modules as a percentage of the total PV market in year t [%]

4.1.5 Decommissioning pattern

Based on the weight of historic and expected future added PV capacity, using a decommissioning pattern, the mass of PV waste that can be expected in future years is estimated.

IRENA's decommissioning probability scenarios

The annual probability of decommissioning is based on the regular-loss probability scenario, developed by the International Renewable Energy Agency (IRENA) (IRENA, 2016). One of IRENA's probability scenarios is chosen, as their probability scenarios are the most widely utilized decommissioning probability scenarios in the field of PV waste stream forecasting and the necessary input data is readily available (Mahmoudi, Huda, & Behnia, 2019; Santos & Alonso-García, 2018). They usually investigate future waste streams using both an early-and regular-loss scenario. Both scenarios assume an average solar panel lifetime of 30 years, which is derived from extensive research by Frischknecht, Heath, Raugei, Sinha, and de Wild-Scholten (2016). Furthermore, based on durability data, a 99.99 percent probability of failure is presumed after 40 years (Greenspec, 2020).

The early-loss scenario differs from the regular-loss scenario as it assumes higher probability of early decommissioning due to infant, mid-life and wear-out failures before the characteristic lifetime. The probabilities for these losses are based on reports by the IEA and IRENA, and are incorporated in the shape parameter of the weibull function, which will be discussed below (IEA-PVPS, 2014; IRENA, 2016).

Weibull distribution

Both scenarios use a Weibull distribution to determine the decommissioning pattern throughout the years. As discussed in chapter 2, the Weibull distribution is a common tool used to analyse PV module failure overtime (Mahmoudi, Huda, Alavi, et al., 2019). The Weibull function that is used to describe both scenarios is shown in equation 7. Equation 7 provides the cumulative decommissioning probability over a certain time interval, while equation 8, gives the annual probability of decommissioning in a given year.

$$p(l) = 1 - e^{-(\frac{l}{\tau})^{\beta}} \tag{7}$$

p(l) : Cumulative probability of solar panel failure

l : Lifetime in years [y], l=0 at the year of installation

τ: Scale parameter

β: Shape parameter

$$p_{\mathrm{a}}(l) = p(l) - p(l-1) \tag{8}$$

$p_a(l)$: The annual probability of decommissioning in a given year of a PV panels lifetime

The scale parameter (τ) represents the characteristic lifetime of a solar module, while the shape parameter (β) defines how module failures typically develop over time l. A lower shape parameter value results in a higher likelihood of decommissioning in the early stages of a PV panel's lifetime, while a higher shape parameter value results in a higher probability of decommissioning near the characteristic lifetime (Santos & Alonso-García, 2018). For both the early-and regular-loss scenario the scale parameter is set at 30. Based on research carried out by IRENA, the shape parameter of the early-loss scenario is set at 2.4928 and for the regular loss-scenario at 5 (IRENA, 2016).

Figure 7 and 8 show the cumulative and annual Weibull distribution for the early-and regular-loss scenario. The early-loss scenario largely represents waste streams consisting of 'premature module failures'. Early PV module defects often present opportunities for reparation or reuse (IRENA, 2016). Restored PV modules can be sold again on the secondhand market for a reduced price. As long as modules can still be repaired it is often more economical to repair and reuse instead of recycle. As this study focuses on recycling rather than reuse, the early-loss scenario will not be considered. Since the regular-loss scenario is expected to better represent the actual recycling market than the early-loss scenario, only the regular-loss scenario is investigated.

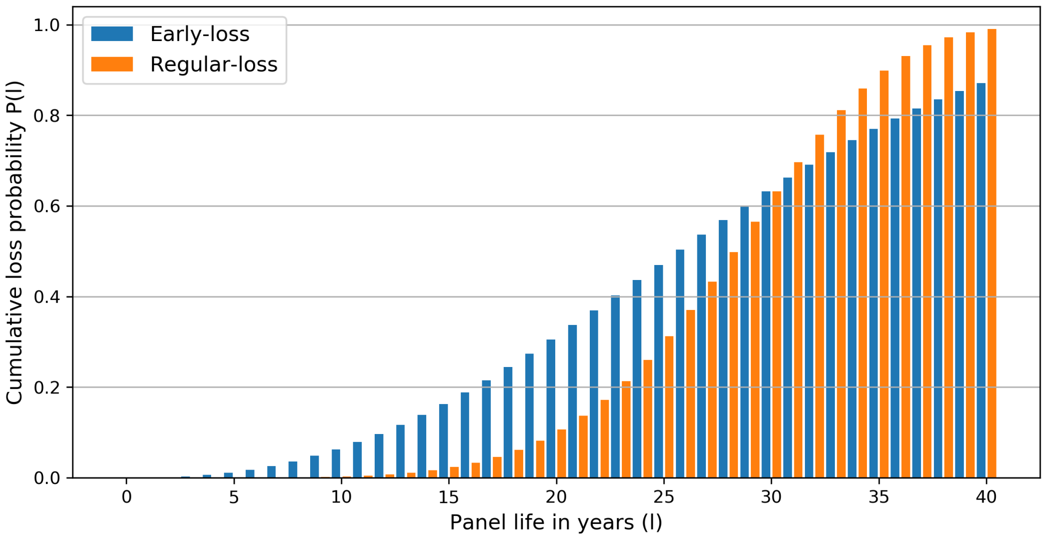


Figure 7: Cumulative Weibull distribution early-and regular-loss scenario, based on data from IRENA (2016).

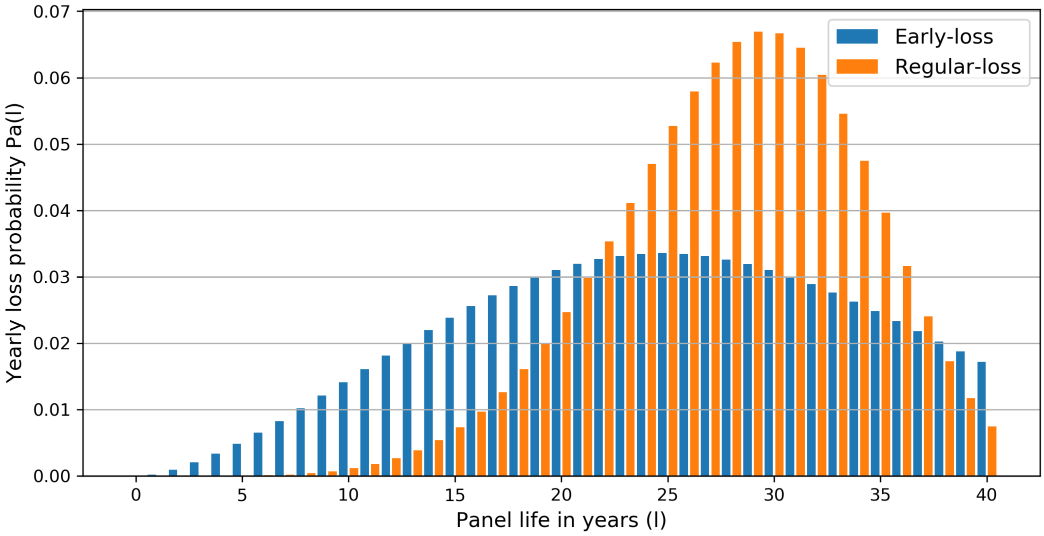


Figure 8: Annual Weibull distribution early-and regular-loss scenario, based on data from IRENA (2016).

By multiplying the outcome of the Weibull function with the weight of the added capacity in every year (2000-2049), the annual and cumulative tonnes of material waste expected in the future are calculated (equation 9 and 10).

$$M_{\text{dec}}(t) = \sum_{y=2000}^{t} \left(M_{\text{add c-Si}}(y) \times p_{\text{a}}(t-y)\right) \tag{9}$$

M_{dec} (t) : The mass of decommissioned panels in year t [kt]

$M_{\text{add c-Si (y)}}$: The added PV capacity in mass, added in year y [kt]

$$M_{\text{dec '21-'50}} = \sum_{t=2021}^{2050} M_{\text{dec}}(t) \tag{10}$$

$M_{\text{dec '21-'50}}$: The cumulative amount of decommissioned panels from 2021 to 2050 [kt]

4.1.6 Material composition

To estimate the weight of the various materials that are present in the PV waste stream, the average material composition of silicon panels per tonne of waste is added to the data-set. The expected future silicon PV waste is multiplied with the average material composition, to calculate the weight of all annual expected material streams (e.g. aluminium, silver, glass, copper etc.) (equation 11). The average material composition of silicon solar panels is shown in table 2. The results will be used in the economic potential assessment to calculate the value of the PV waste.

Table 2: Average material composition of c-Si PV waste (Latunussa et al., 2016)

Material inventory	**Mass share c-Si PV waste** [%]
Glass	70
Aluminium	18.5
EVA	5.1
Silicon	3.65
PVF	1.5
PVC	0.683
Copper	0.461
Silver	0.053
Lead	0.027
Tin	0.027

$$M_{\mathrm{mat}}(t) = M_{\mathrm{dec}}(t) \times \frac{S_{\mathrm{mat}}}{100\%} \tag{11}$$

M_{mat} (t) : Mass of the materials that are contained in the PV waste in a given year [kt]

S_{mat} : The mass share of the materials, a percentage of the total PV waste [%]

(mat = glass, aluminium, EVA ... etc.)

4.1.7 Assumptions

As assessing the PV waste streams of a continent can be a comprehensive task, numerous simplifications have to be made to successfully carry out the waste stream assessment. The assumptions used to do the analysis are listed below:

- An electricity demand estimation for 2050 is used to calculate the future installed capacity scenarios.
- To investigate the effect of future installed capacity on emerging waste streams, multiple scenarios are used. Probably none of the scenarios sketched in this project will exactly predict the future. However, they do give us a good idea of a broad spectrum of possible future scenarios and their effect on the recycling market.
- To calculate expected installed PV capacity in the future scenarios an average PV capacity factor of 0.15 is assumed.
- To calculate the annually added installed capacity from 2021-2049, it is assumed that the installed capacity grows linearly in the business-as-usual scenario and exponentially in the moderate growth and optimistic scenarios.
- The weight and material composition of the various types of PV panels is based on averages.
- It is assumed that the average weight and material composition of future installed capacity is similar to current installed capacity.
- The European c-Si PV market share is assumed to be similar to the global average.
- It is assumed that the solar panel decommissioning behaviour will develop according to the regular-loss probability scenario.
- It is assumed that all decommissioned modules are ready to be recycled, while a certain percentage might actually still be fit for repair and reuse.

Simplifications are an inherent part of modelling and well considered assumptions are necessary to keep the waste stream assessment within the scope of the project. The intention of the waste stream forecast is not to be highly accurate but to be useful to do rough estimations. The assumptions listed above make it possible to simplify reality, in order to get a feeling for the order of magnitude of the PV waste recycling market in Europe.

4.2 Economic potential assessment

Based on the results of the waste stream assessment, the economic potential of the future PV recycling market will be examined. As described in chapter 2, the economic potential is based on economic **value of recovered material** and estimated **total recycling costs**.

4.2.1 Value of recovered material

The economic value of the PV material streams is effected by the following variables:

- The waste volume (result of waste stream assessment)
- Material composition (determined in waste stream assessment)
- Average recycling yields
- Material prices

The expected PV *'waste volume'* and average *'material composition'* are estimated and determined in the first part of the model. The other two variables, *'recycling yields'* and *'material prices'*, will be discussed below.

Recycling yields

In the model, two recovery rate scenarios are used to analyse the value of the material streams. One scenario is based on current recycling yields (*baseline scenario*) and the other is based on recycling yields achieved with the more advanced and experimental *FRELP recycling process*, which has been discussed in chapter 3.

Baseline scenario

Currently, in the best case scenario, PV recycling facilities recycle only the glass shield and aluminium frame. Although many general purpose facilities are not able to recycle the glass with a high yield or purity, the recycling yields of the baseline recycling process in the model are, based on the recycling facilities that are able to do so.

FRELP process

With the FRELP process it is possible to recycle all value driving materials, at high recycling yields. Besides recycling glass and aluminium, also copper, silicon and silver can be recycled through the FRELP process.

Table 3 provides an overview of the recovery rates of the baseline recycling process and the FRELP process. The recycling yields are based on data obtained from Ramon (2021) and Heath et al. (2020). Only the recycling of glass, aluminium, silicon, copper and silver is analysed. As the remaining materials are not expected to ever be worth enough to add any real value to the recycling process, they are not taken into account. According to Lempkowicz (2021), recycling these materials is significantly more expensive and also less eco-friendly than using the remaining materials in incineration to create energy.

Table 3: Recycling yields.

Materials	Baseline recycling process [%]	FRELP process [%]
Glass	98	98
Aluminium	94.4	94.4
Silicon	0	97
Copper	0	97
Silver	0	94

Material prices

The value of the material is based on current commodity prices (IndexMundi, 2021). Notably, the metals are not pure when they are sold to the metal refineries. Therefore, they are generally not sold for the full commodity price. According to Luo (2021), on average 75 percent of the commodity price is payed for the scrap metals recovered from the PV recycling process.

As the model estimates PV waste volumes up until 2050, many variables can influence material value in the mean time. For example, future scarcity of silver might lead to a significant increase in its price, while an abundance of aluminium could cause a collapse of its market value. It is difficult to predict future material prices, especially when looking decades ahead. Therefore, to take into account fluctuating market prices, a +/- 20 percent market price error margin is included in the model. The estimated value of recovered material is shown in table 4.

Table 4: Recovered material value.

Materials	Current prices [€/kg]	+ 20 percent [€/kg]	- 20 percent [€/kg]
Silver	561.25	673.50	449.00
Copper	3.81	4.57	3.00
Silicon	1.87	2.24	1.50
Aluminium	1.19	1.42	0.95
Glass	0.10	1.20	0.08

Based on the average material composition, recycling yields and material prices, the value of a tonne of c-Si PV waste is calculated (€/t) (equation 12). This is multiplied with the expected PV waste volumes, to estimate the annual and cumulative market value between 2020-2050 in various scenarios.

$$V_{\text{tot}} = \sum_{mat} \left(V_{\text{mat}} \times \frac{Y_{\text{mat}}}{100\%} \times \frac{S_{\text{mat}}}{100\%} \right) \tag{12}$$

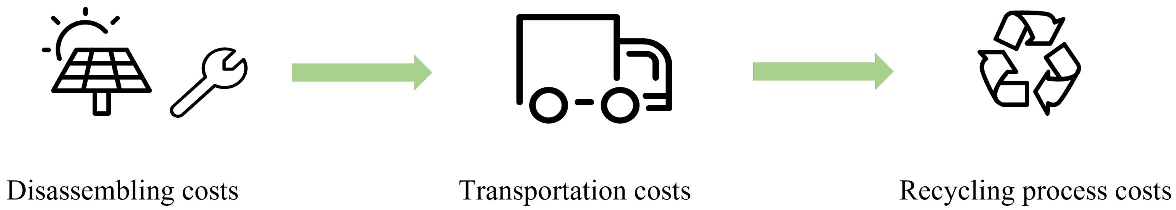
V_{tot} : Total value of the recovered material of one tonne of PV waste [€/t]

V_{mat} : Value of the various materials [€/t]

Y_{mat} : Recycling yields of the various materials [%]

4.2.2 Total recycling costs

The costs for the decommissioning and recycling process are divided into three categories: disassembling costs, transportation costs and recycling process costs. The FRELP recycling process and corresponding data is used in the model to investigate future recycling process costs. The cost categories, corresponding variables and modelling decisions are explained below.



Disassembling costs

In order to estimate future disassembling costs, first the current average disassembling costs are determined. Next, based on multiple scaling factors, three cost reduction scenarios are designed.

Current disassembling costs

According to NYSEDA (2021), the current disassembling costs for a 1 MW PV plant are approximately 29 k$[1]. In order to use this in the model, the value is converted to euros per tonne of PV waste (€/t). The conversion is based on the average weight (15.75 kg/m^2), nominal power (153 Wp/m^2) and an exchange rate of 0.8 $/€ (Domínguez & Geyer, 2017; Xe, 2021). Based on this calculation, the average costs are approximately 235 €/t for solar panel disassembling (C_d). Although, disassembling costs will slightly vary depending on project size, location and complexity, 235 €/t will be used as a rough estimate.

[1] 29 k$ = $ 29·10^3

Economies of scale in disassembling costs

As the PV recycling market increases, the disassembling costs are expected to decrease as a consequence of learning effects, technology advancement and other economies of scale. Using equation 13, based on current disassembling costs, the current recycling market size, the expected size of the future recycling market and a certain scale factor, future disassembling costs are estimated. The current average disassembling costs (C_{d1}) have been established above. The current PV recycling market size (Q_1) and expected size of the future recycling market (Q_2) are based on the output of the waste stream assessment. The annual size of the market is assumed to be proportional to the PV waste volume in that same year.

The scaling factor (x) determines the decrease of average costs relative to the increase in market size. In case of an increase in market size, a low scaling factor results in a strong decrease of average costs, while a high scaling factor results in a weak decrease of average costs. The chosen values are discussed below.

$$C_{\mathrm{d2}} = C_{\mathrm{d1}} \times \left(\frac{Q_2}{Q_1}\right)^x \tag{13}$$

C_{d1} : Current disassembling costs (2021) [€]

C_{d2} : Expected future disassembling costs in a given year [€]

Q_1 : Current size of the PV recycling market (2021) [t]

Q_2 : Estimated future size of the PV recycling market in a given year [t]

x: Scaling factor

Cost reduction scenarios

Three cost reduction scenarios, with varying scaling factors, will be investigated in the model: a *weak decline* in costs (s1), *average decline* in costs (s2) and *strong decline* in costs scenario (s3).

Since the PV recycling market is still in its infant phase, there are no scaling factors (x) available for the disassembling process. For the recycling process, scaling factors often encountered in the process industry (0.85 and 0.5) and in scaling research in general (0.6), will be used (Dysert & Pickett, 2005; Whitesides, 2005). These are explained in more detail later in this chapter when the process costs are discussed.

However, as disassembling is rather labor intensive, the scaling effect is assumed have less of an impact on disassembling costs as it is expected to have on the actual recycling process, which is a more capital intensive process. Therefore, the scaling factors used to estimate the recycling process costs are increased by 20 percent for the calculations on disassembling costs. The scale factors for disassembling costs are set at 1 for the weak decline in cost scenario, 0.8 for the average decline in cost scenario and 0.6 for the strong decline in cost scenario. This means that in the weak decline in cost scenario, there is no decline in disassembling costs as there is a linear relationship between market size and costs.

Equation 13 provides the total disassembling costs of the future PV recycling industry, however in order to compare the recycling costs with the recovered material value, we are interested in the disassembling costs per tonne of PV waste. Therefore, total disassembling costs are divided by the market size (volume of collected PV waste), to calculate the new average disassembling costs per tonne of PV waste (equation 14).

$$C_{\mathrm{d}} = \frac{C_{\mathrm{d2}}}{Q_2} \tag{14}$$

C_{d} : Average cost of disassembling in a given year [€/t]

Transportation costs

As mentioned in chapter 3, in order to estimate future transportation costs, two scenarios are investigated in the model. The first is transportation without pre-treatment and the second is transportation with pre-treatment (figure 9). The scenario without pre-treatment, assumes direct transportation from the recycling plants to the recycling facility. The scenario with pre-treatment, first ships panels to a nearby collection point, where the first step of the FRELP process is carried out. Afterwards the remaining 'material sandwich' is sent to the recycling facility.

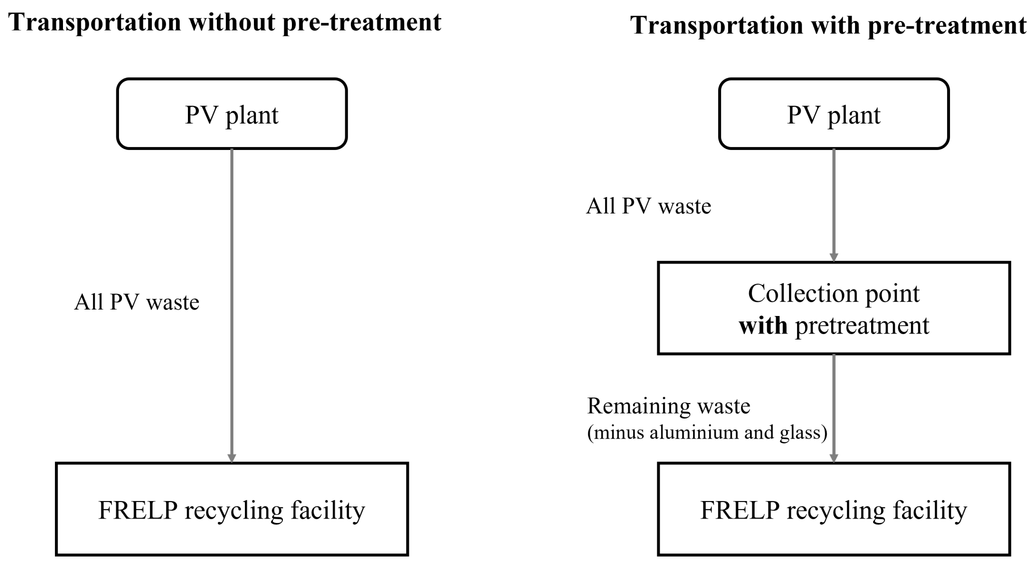


Figure 9: Transportation cost scenarios.

Transportation without pre-treatment

As collection points are skipped in the scenario without pre-treatment, only transport costs incurred from the PV plant to the recycling facility are taken into account. To calculate the average transportation costs without pre-treatment, the average costs per tonne per kilometre is determined and a method to calculate the average transportation distance is established.

Transportation cost per tonne per kilometre

In the model, the average transportation costs are linearly correlated with the average distance from a PV power plant to a PV recycling facility (equation 15). According to Panteia (2020), the average cost of freight transportation is 0.366 €/(t·km). The transportation cost per tonne per kilometre are not expected to change due to an increase in market size, therefore the scaling relationship between size and costs in transportation is assumed to be linear. The average distance however, is influenced by the number of recycling facilities operating throughout Europe in the future. More facilities results in a lower average distance and therefore lower average transportation costs. Currently, there are almost no recycling facilities specialized in PV recycling operating in Europe. As they are almost non-existent, current recycling locations are not included in the model. As PV waste streams increase over the years a growing number of recycling facilities will be necessary to process increasing waste volumes.

$$C_{\mathrm{t\ WOT}} = C_{\mathrm{dis}} \times d \tag{15}$$

$C_{\mathrm{t\ WOT}}$: Average cost of transportation without pre-treatment in a given year [€/t]

C_{dis} : Cost per tonne per kilometre [€/(t·km)]

d : Average distance from a PV plant to a (FRELP) recycling facility in a given year [km]

Determining the number of recycling facilities

As discussed in chapter 3, it is assumed that the FRELP recycling process is commercially interesting when a facility can process 20 kt tonnes of c-Si waste per year. An 85 percent PV waste collection rate is assumed in the model (see chapter 3). Therefore, in the model we assume that the amount of PV recycling facilities operating in a given year, is calculated by dividing the annually collected PV waste (PV waste multiplied with the collection rate factor) by 20 kt (equation 16). It is assumed that every facility in Europe operates at 20 kt/y. New recycling facilities are added to the recycling network as the waste volume grows.

$$F(t) = \frac{M_{\mathrm{dec}}(t)}{s} \times \frac{K}{100\%} \tag{16}$$

F(t) : Number of recycling facilities in a given year

s : Size / annual capacity of the FRELP recycling facility [kt]

K : PV waste collection rate [%]

Locating the first facility

To minimize transportation costs, the 'first' facility will be located roughly at the center of gravity of installed PV capacity in Europe. With more than 40 percent of the current installed capacity in Europe, Germany is the PV market leader. As Germany is also located relatively centrally in Europe, it is assumed that the first recycling facility is located in Germany. Although, a higher density of PV capacity is found in the southern areas of countries or along the coast, for simplicity, the solar PV capacity of each individual member state, is assumed to be distributed evenly throughout the country. Therefore, to minimize average transportation costs, the first recycling facility is located in the center of Germany.

Determining the distance to the first facility

To calculate the average distance from a PV plant to this first PV recycling location, for modelling purposes the country is assumed to be a square. The average distance from all PV plants in Germany to the center of the country is assumed to be roughly halve the average distance from the center to the borders of the country.

Furthermore, Europe is also assumed to have the mathematical properties of a square. Therefore, for the remaining European PV plants, the average distance to this recycling facility, is half the average distance from the center of Germany to the outer edges of Europe.

For a visualization please see the left square in figure 10. Although the average distance in a square is actually a bit more than 1/2 x, for modelling purposes we assume this is roughly the average distance. Google Maps in 'driving' mode is used to do estimations of the distances. Using equation 17, a rough estimation is made of the average distance of all PV plants in Europe to the 'first' PV recycling facility, located in the center of Germany.

$$d_{\mathrm{F=1}} = \frac{S_{\mathrm{PV\ DE}}}{100\%} \times d_{\mathrm{DE}} + \frac{S_{\mathrm{PV\ restEU}}}{100\%} \times d_{\mathrm{EU}} \tag{17}$$

$\mathrm{d_{F=1}}$: Rough estimation of the average distance of all PV plants in Europe to the first FRELP recycling facility [km] *If F=1,* $d=d_{F=1}$

$\mathrm{S_{PV\ DE}}$: PV market share of Germany [%]

d_{DE} : Rough estimation of the average distance of all PV plants in Germany to the first FRELP recycling facility located in the middle of the country [km]

$S_{PV\ restEU}$: PV market share of the remaining EU member states [%]

d_{EU} : Rough estimation of the average distance of all PV plants in the remaining EU member states to the first FRELP recycling facility located in Germany [km]

Decrease in transportation distance with every new facility

It is assumed that a new recycling facility is opened for every extra 20 kt of annually collected PV waste. When a new facility is added to the model, the average distance decreases. The new average distance is also calculated based on the idea that Europe is a square. Although this is a large simplification, it allows us to roughly estimate the average decrease of transportation costs with every new recycling facility. Based on this notion the average distance is divided by two every time the number of new recycling facilities is multiplied with a factor four (equation 18). As shown in figure 10, the first 4 new recycling facilities together decrease the average distance by half (4 x 12.5%). To cut the new average distance in half, 16 new facilities are needed (4×4=16). While for the next 50 percent decrease in travel distance, 64 new facilities are necessary (16×4=64), and so on.

The effect of an additional recycling facility on the average travel distance becomes smaller as the number of facilities increase. While one of the first 4 new recycling facilities decreases the average recycling costs with approximately 12.5 percent, any of the next 16 new recycling plants, only decreases the average transportation costs by approximately 3.1 percent. Any of the following 64 facilities only decreases the average transportation costs with roughly 0.8 percent. Figure 11, depicts the decrease in transportation cost as a function of the number of recycling facilities operating in Europe.

$$d = \frac{d_{\mathrm{F=1}}}{2^i} \tag{18}$$

i : Is an integer that represents the steps for the reduction of the average distance by half, every time the number of new facilities is multiplied by a factor 4

i = 1: 4 new facilities (F = 1 + 4)

i = 2: 16 new facilities (F = 1 + 4 + 16)

i = 3: 64 new facilities (F = 1 + 4 + 16 + 64)

etc.

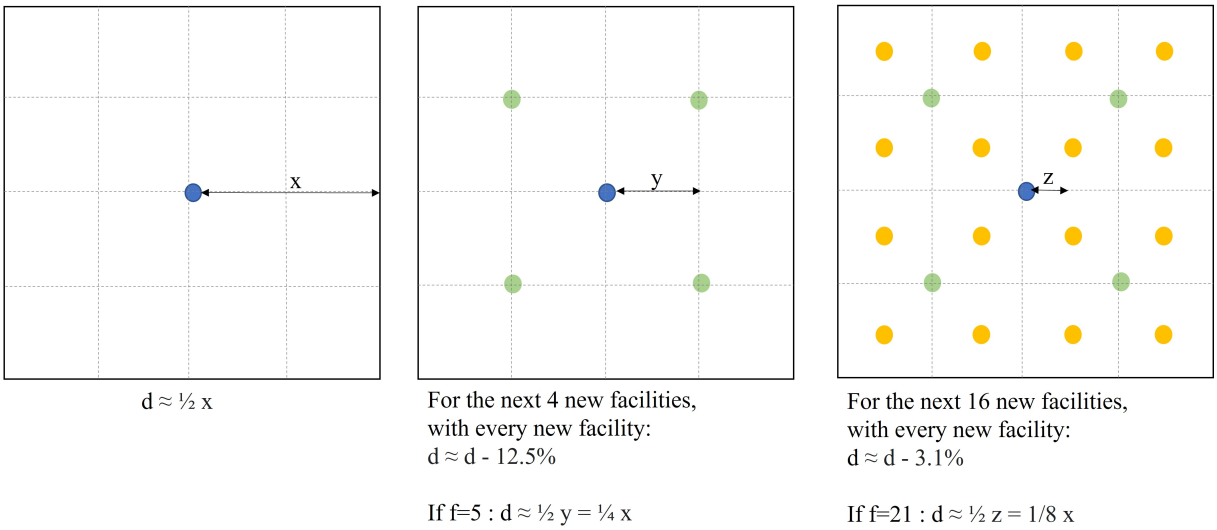


Figure 10: Visualization of the decrease in average distance (d) with every new recycling facility added in Europe.

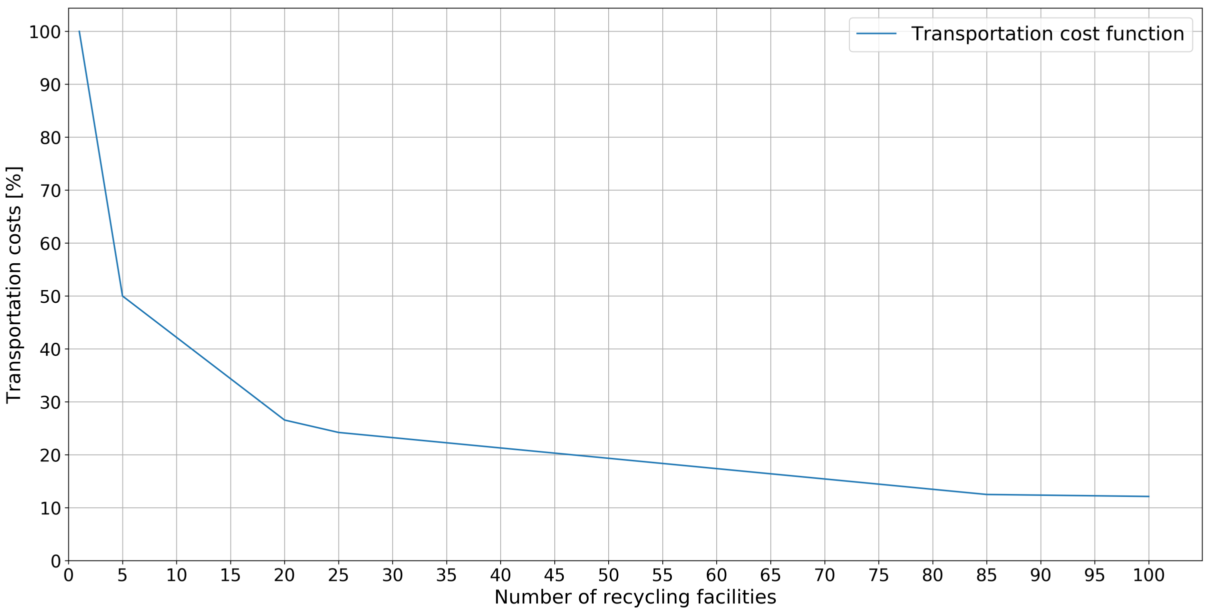


Figure 11: Decrease in transportation costs (%) due to increase in amount of recycling facilities.

Transportation with pre-treatment

In the scenario with pre-treatment the transportation costs consist of shipping the waste from the PV plants to the collection points, and shipping the remaining waste from the collection points to the PV recycling facilities.

From PV plant to collection point

According to Ardente et al. (2019), the distance from a PV plant to a nearby collection point is approximately 100 km. As the average cost of freight transportation is 0.366 €/(t·km) (Panteia, 2020), the average transportation costs from the PV plant to the collection point ($C_{t\ a}$) is estimated to be 36.6 €/t. The average costs for transportation from a PV plant to a collection point is assumed to be fixed.

From collection point to PV recycling facility

The collection points are found in areas with high installed PV capacity. Thus, it is assumed that the average distance from the collection points to the recycling facilities is roughly the same as the average distance from the PV plants to the recycling facilities. However, as the first step of the FRELP process is carried out at the collection points, taking off the aluminium frame and glass shield, the weight of the PV waste transported to the PV recycling facilities is significantly less in the pre-treatment scenario. As transportation costs are linearly correlated with the weight of the waste, the transportation costs covering transport from the collection points to the recycling facility, decrease by the same percentage. The cost of shipping the remaining waste from a collection point to a recycling facility is calculated using equation 19.

The **total transportation costs** in a scenario with pre-treatment is calculated by adding the average costs of shipping from the PV plants to the collection points (36.6 €/t), to the average cost of shipping from the collection points to the recycling facilities (equation 20).

$$C_{\mathrm{t\ b}} = C_{\mathrm{dis}} \times d_{\mathrm{b}} \times M_{\mathrm{f}} \tag{19}$$

- $C_{t\ b}$: Average cost of transport from a collection point to a (FRELP) recycling facility in a given year [€/t] ***(note:** to be able to compare the two scenarios, the costs are calculated for a tonne of 'initial' PV waste, the actual waste transported from the collection points to the recycling facility is less as part of the waste is pre-treated at the collection point)*
- d_b : Average distance from a collection point to a (FRELP) recycling facility in a given year [km] *('d_b' in the scenario with pre-treatment is the same as 'd' in the scenario without pre-treatment)*
- M_f : Fraction of the remaining waste

$$C_{\text{t WT}} = C_{\text{t a}} + C_{\text{t b}} \tag{20}$$

$C_{\text{t WT}}$: Average cost of transportation with pre-treatment in a given year [€/t]

$C_{\text{t a}}$: Average cost of transport from a PV plant to a collection point [€/t]

Recycling process costs

The process costs in the model are based on FRELP data. To estimate future recycling process costs, first the current FRELP recycling process costs are determined. Next, three scale factors are identified that are used to simulate the process cost reduction.

Current FRELP process costs

Based on data retrieved from Ramon (2021), currently the average recycling process costs of the FRELP process are estimated to be 461 €/t, in case a capacity of at least 20 kt/y is reached. Step one of the FRELP process, extracting the aluminium and glass, costs approximately 170 €/t. Step two, extracting the silicon, is estimated to be 67 €/t. Step three, recovering the silver and remaining copper, is expected to cost around 225 €/t. The process costs include: electricity bills, maintenance costs, landfill costs (to safely dispose the remaining waste), labor costs, commercial costs and overhead costs.

Economies of scale in recycling process costs

As a result of external economies of scale, the process costs are expected to decrease as the PV waste market increases. With equation 21, introduced earlier in this chapter, crude estimations of future recycling process costs are made.

$$C_{\text{p2}} = C_{\text{p1}} \times \left(\frac{Q_2}{Q_1}\right)^x \tag{21}$$

C_{p1} : Current process costs (2021) [€]

C_{p2} : Expected future process costs in a given year [€]

In process industries the scaling factor (x) has shown to vary between 0.5 and 0.85 (Dysert & Pickett, 2005). However, when an industry is relatively new, as is the case with the PV recycling industry, often there is no real information available about the average scaling factor. In this case the rule of 'six-tenths' is used to make crude estimations about future costs. Based on large quantities of cost data in various industries, a scaling factor of 0.6 has shown to provide very satisfactory results when only a rough approximation is necessary (Whitesides, 2005).

To get a better understanding of possible process cost reduction, the scaling factors introduced above are used in the three cost reduction scenarios in the model. A scaling factor of 0.85 for the *weak decline* in costs scenario, 0.6 for the *average decline* in costs scenario and 0.5 for the *strong decline* in costs scenario, will be used to estimate future recycling process costs. Similar as with the decommissioning costs, equation 22 is used to calculate the average process costs per tonne of PV waste.

$$C_{\mathrm{p}} = \frac{C_{\mathrm{p2}}}{Q_2} \tag{22}$$

C_{p} : Average FRELP recycling process cost in a given year [€/t]

The total recycling costs of one tonne of PV waste (C_{tot}) are calculated by adding together the disassembling costs (C_{d}), transportation costs (C_{t}) and the process costs (C_{p}), in a given year.

4.2.3 Economic profitability

To investigate the possibility for a profit in the future PV recycling industry, the material value estimates (€/t) are compared with the expected total decommissioning and recycling costs (€/t) in the years between 2021-2050, for the various scenarios. The model is meant as a tool to investigate the economic potential of the PV recycling market and to analyse in what scenarios it is likely that the PV recycling industry will become profitable in the future.

4.2.4 Assumptions

The assumptions made to carry out the economic potential assessment are shown below:

- Future material prices are assumed to be +/- 20 percent of current prices.
- Disassembling costs for Europe are assumed to be similar as in the United States.
- The average transportation costs are linearly correlated with the average distance. The scaling relationship between market size and costs in transportation is assumed to be linear as well. Which means no scaling effects.
- The average transport distance is influenced by the amount of recycling facilities operating in Europe.
- The recycling facilities are assumed to operate at 20 kt. For every 20 kt annually 'collected' waste a new facility is added to the model.
- An 85 percent waste collection rate is assumed in the model.
- The 'first' FRELP facility is assumed to be located roughly at the center of gravity of installed PV capacity in Europe (center of Germany).
- The PV capacity of each country is assumed to be evenly distributed over the country.
- To estimate the average distance from a PV plant to the first recycling facility, Europe is assumed to be a square.
- The average distance from a PV plant to a recycling facility is divided by two, every time the amount of new recycling facilities is multiplied with a factor four.
- The distance from a PV plant to a nearby collection point is 100km and assumed to be fixed.
- The average distance from collection points to the recycling facilities is assumed to be the same as the average distance from PV plants to the recycling facilities.
- The FRELP recycling yields are based on laboratory results and are assumed to be similar on a commercial scale.
- Process costs and disassembling costs are assumed to be effected by economies of scale. Based on related markets and the rule of 'six-tenths', three scaling factor scenarios are investigated. The scaling factors used in the scenarios for disassembling costs are assumed to be 20 percent higher than the ones used for process costs.
- The annual size of the PV market is assumed to be proportional to the PV waste volume in the same year.
- Total recycling costs (C_{tot}) is assumed to be the sum of disassembling costs (C_d), transportation costs (C_t) and the process costs (C_p), in a given year.

Based on the assumptions listed above, it is possible to make rough estimations and get a better understanding of the economic potential of the PV recycling market in future years.

4.3 Data sources

The following main data sources are used in the model in order to do the waste stream and recycling cost forecast:

- Historic PV installation capacity in Europe: Solar-Power Europe (SPE, 2015)
- Total electricity demand 2050: European Commission (EC, 2018)
- Average capacity factor Europe: IEA (2018)
- Global market share of c-Si per year: Monier and Hestin (2011), Weckend et al. (2016) and, Domínguez and Geyer (2017)
- Average weight and nominal power for c-Si technology: Domínguez and Geyer (2017)
- Parameter values Weibull function based on PV panel loss probability: IEA (2015) and IRENA (2016)
- Average material composition: Latunussa et al. (2016)
- Recycling yields: Heath et al. (2020) and Ramon (2021)
- Commodity prices: IndexMundi (2021)
- Disassembling costs: NYSEDA (2021)
- Average transportation costs: Panteia (2020)
- Capacity of a commercial FRELP facility: Ramon (2021)
- PV waste collection rate: European Commission (EC, 2018)
- Average distance from PV plants to a nearby collection point: Ardente et al. (2019).
- FRELP process costs: Ramon (2021)
- Scaling factors: Dysert and Pickett (2005) and, Whitesides (2005)

4.4 Validation

This section briefly discusses the validation process of the waste stream forecast model, in order to confirm that the model suits the purpose of the research and the results can be considered realistic.

An obvious way of validating a model is to do an experiment and compare the results of the model to reality (Nikolic et al., 2019). This gives an indication of how well the model represents real life. However, in this particular case, a forecast of future events is done. As these events have not taken place yet, the results cannot simply be compared to reality. Therefore, in an attempt to validate the model, the input data, functions and results have been compared to other academic PV waste stream assessments and have been examined by PV recycling experts.

The outcome of **waste stream assessment** of this study has been compared to studies carried out by Domínguez and Geyer (2019) and (Mahmoudi, Huda, & Behnia, 2019), for the the United States and Australia respectively. The United States has currently approximately 49 GW of installed PV capacity and is expecting 4.72 Mt of PV waste up until 2050 (Domínguez & Geyer, 2019). Australia had roughly 10 GW of installed capacity in 2018, while the expected cumulative PV waste volume in 2050 is approximately 0.8 Mt (Mahmoudi, Huda, & Behnia, 2019). In 2020, Europe has roughly 140 GW of installed capacity (SolarPowerEurope, 2020). According to the model, based on current installed capacity, the cumulative PV waste expected up until 2050 is approximately 12 Mt. The expected waste volumes relative to the corresponding installed capacity of each country, are of the same order of magnitude. The installed capacity of the United States is approximately 3 times smaller than that of Europe, therefore you would expect the cumulative PV waste to also be approximately 3 times smaller, which is the case. The installed capacity of Australia is approximately 14 times smaller than that of Europe, also the expected PV waste is roughly 14 times less than in Europe. Although there are some minor differences in the ratios between installed capacity and expected PV waste, they can be explained by different modelling decisions and different PV installation patterns. This shows that the waste volume is probably of a realistic order of magnitude.

The **economic potential assessment** cannot really be compared to other research projects as, to the best of our knowledge, it has not been done in a similar way by other PV waste stream researchers. In an attempt to partly check validity of the economic potential assessment, a PV recycling expert was contacted and involved in the process. Ramon (2021), shared information on their estimations regarding recycling yields and total recovered material value. The yields were used in the model and the total recovered material value corresponded closely with the model output. Their recovered material value is estimated to be 690 €/t, while the waste stream forecast model, used in this study, estimates the recovered material at 650 €/t, which is only a 6 percent difference. The difference can be explained due to slightly different commodity prices and the fact that the cables and junction box were included in their value estimate, while they were excluded from this study. The current recycling costs are based on various sources. Although, the future recycling costs estimates could not really be validated by the literature or experts, the scaling law used to estimate future costs, is a method that has been successfully used in various other fields of research.

4.5 Sensitivity analysis

To get a better idea of the inner workings of the model and the level of influence certain variables have on the results, a sensitivity analysis was carried out. The analysis showed that changes regarding the commodity price, mass or recycling yield of *silver*, and adjustments to the *scaling factors*, have the most significant impact on the result of the model.

Silver

Silver is clearly the most valuable material found in the PV waste. If, on a commercial scale, the recycling yield of silver turns out to be only halve of what is achieved in the laboratory tests, the total value of the recovered material is reduced with 22 percent. This decrease in recycling yield makes profitability in the 'weak decline in costs scenario' impossible. In comparison, if the same is true for any of the other value drivers: copper, silicon, glass or aluminium, the total value of the recovered material is reduced with 1, 5, 5 or 16 percent respectively. The recycling yield of aluminium, also has a significant effect on the total recycling costs. However, the aluminium frame is considered the easiest part to recover, as it can be disassembled mechanically and no complex recycling methods are needed. Therefore, the recycling yield of aluminium is widely considered to be close to a 100 percent. This is definitely not the case for silver, as the methods used to extract the silver from the PV sandwich are still experimental and in development. Therefore, on a commercial scale, silver recycling yields might be different than the values used in the model. Although, the sensitivity of the total material value to the recycling yields of silver and aluminium are somewhat comparable, the probability of the recycling yields being different in reality is rather high for silver and almost non-existent for aluminium.

Furthermore, if the recycling yield of silver stays the same, but the average amount of silver in a tonne of PV waste is decreased by half, changing from 0.053 percent to 0.026 percent, a similar decrease in overall value is experienced. In this case a 0.027 percent error of in the average material composition estimate, would mean a 22 percent decrease in total market value. A remarkably small estimation error results in a decrease of the total market value of millions of euros.

Scaling factors

Lastly, the outcome of the results are rather sensitive to adjustments in the scaling factors used to estimate future recycling costs. The difference between a scaling factor of 0.5 and 0.6 for disassembling or process costs, can result in a 40 percent cost difference in 2050. As the actual scaling factors for the PV recycling industry are unknown, they are based on scaling factors in the process industry. However, these could turn out to be different in the PV recycling market. In order to deal with this insecurity, three scenarios, covering a wide variety of scaling effects, are investigated in the model.

Changes in one of the variables described above, can result in a seriously different outcomes. This is important to keep in mind in order to put the results in perspective. The following chapters will discuss the actual results of the waste stream forecast for the various scenarios.

5 Future PV waste volumes and material streams in Europe

This chapter focuses on the expected future PV waste volumes and material streams in the EU and in the individual member states. The aim of this chapter is to provide an overview of the emerging PV waste problem in the EU. First, annual waste volumes in Europe as a whole are illustrated, after which the distribution of PV waste in Europe is analysed. Next, the annual and cumulative waste volumes of the individual member states are discussed. Lastly, based on the average material composition of the PV waste, material streams are considered. The following sub-question will be answered in this section:

> **Sub-question 2:** What PV waste volumes and material streams can be expected in Europe up until 2050?

The waste volume estimations depend on historic installed PV capacity and the future installed capacity scenarios. As discussed in chapter 4, a business-as-usual, moderate growth and strong growth PV penetration scenario are examined in the waste stream forecast model. These scenarios assume a 5, 25 and 50 percent solar PV electricity market share in 2050 in Europe, respectively.

5.1 Annual PV waste in Europe

This paragraph provides insights into the annual PV waste volumes in the EU as a whole. Figure 12 shows the PV decommissioning patterns over the years for the business-as-usual, moderate and strong PV penetration scenarios.

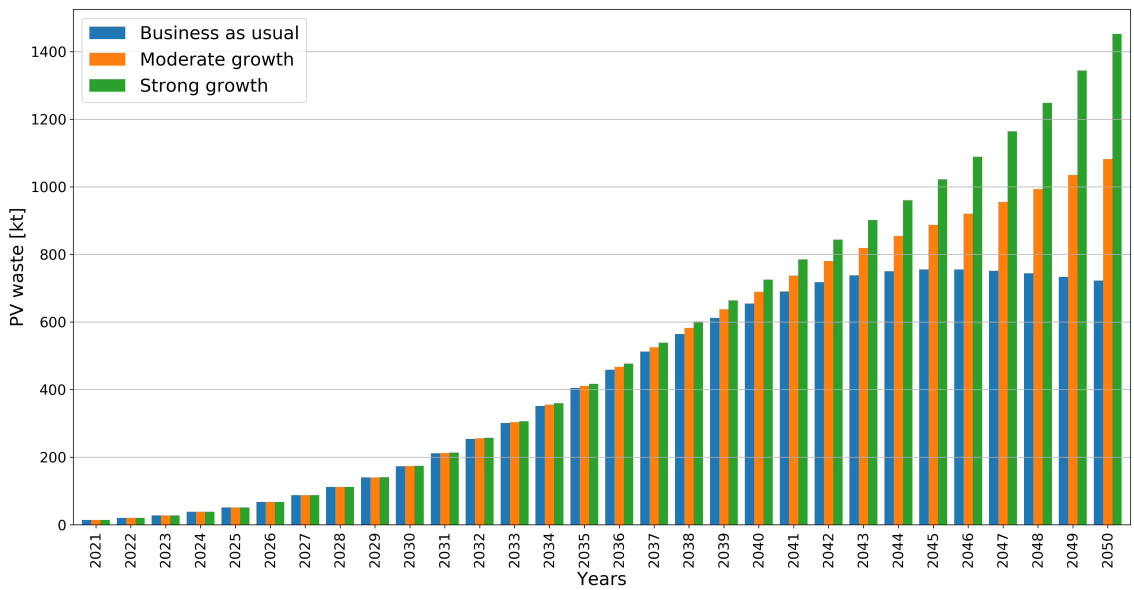


Figure 12: Decommissioning pattern of the business-as-usual, moderate and strong penetration scenario.

Although the annually added PV capacity fluctuates a lot between 2000-2020 (figure 3), this does not result in major fluctuations in waste over the years in the model (figure 12). The Weibull probability function tends to create a rather smooth PV failure profile. However, this could be different in reality, as large solar farms are often decommissioned at ones, potentially causing spikes in waste production.

Comparing the PV penetration scenarios

The scenarios show similar waste volumes up until approximately 2035, after which differences become apparent. In 2037 the difference between the business-as-usual scenario and the strong growth scenario is approximately 5 percent, while in 2040 this difference is already more than 10 percent.

The scenarios are based on the same **historic capacity** and only differ based on expected future installed capacity. This shows that PV EoL management up until 2035 is predominantly shaped by already installed capacity and is not notably affected by future installed capacity. In this sense, the relatively long period between instalment and decommissioning is an advantage for the PV recycling industry, as the industry can estimate the size of the annual market approximately 15 years in advance, without having to speculate about future installed capacity.

In 2050, significant differences between the scenarios are apparent. The annual waste volume of the strong PV penetration scenario (1,450 kt) is more than double the volume expected in the business-as-usual scenario (720 kt). This shows that the annual waste volume around the year 2050 is significantly influenced by **future installed capacity** and cannot simply be estimated based on historic installed capacity alone.

Potential capacity issues in the business-as-usual scenario

The **business-as-usual scenario** has the lowest annual waste volumes in later years and even experiences a small decrease in waste, from the year 2045 onwards. The relatively low annual waste volumes are due to the weak growth of PV capacity between 2021-2050. The decrease in annual waste is a consequence of strong spikes in PV instalment around the years 2011 and 2020 as shown in figure 3, after which annually added capacity stayed relatively low up until 2050. A future in which the business-as-usual scenario becomes reality could cause serious complications for the recycling industry. The initial increase in PV waste followed by a decrease can potentially lead to capacity issues for PV recycling plants. They will be built to process peak waste volumes around 2043, however, they will not be able to run at full capacity in later years when the waste volumes decrease, leading to recycling capacity being unused.

On the other hand, the **moderate growth** and **strong growth** PV penetration scenarios experience a steady increase of PV waste up until 2050. This is caused by the exponential growth of PV capacity expected in these scenarios between 2021-2050. As waste volumes grow in both scenarios, the recycling industry will likely keep growing at a similar rate.

5.2 Country specific waste streams

To get a better understanding of where in Europe most waste volumes will emerge, this section provides insights in country specific waste volumes, focusing on the ten countries with the biggest PV markets in Europe. First the average waste distribution among the European member states is discussed, after which the actual annual and cumulative waste volumes are analysed.

The waste distribution is based solely on historic installed capacity, as this is the only reliable data available for the spread of installed capacity between countries. The distribution of PV capacity among EU member states in future years is based on the average historic PV capacity distribution, and is therefore assumed to stay the same.

5.2.1 PV waste distribution in Europe

The expected PV waste is rather unevenly distributed throughout Europe. Figure 13 provides an overview of the distribution of the cumulative PV waste between 2021-2050. Germany is expecting to produce 40 percent of all PV waste in Europe in this period. Other big PV waste producers are: Italy with 16 percent, Spain with 9 percent and France expecting to cover 8 percent of the total PV waste market. As Germany is clearly the **PV waste hotspot** of Europe for the coming decades, Germany could potentially serve as an example for the other member states regarding effective PV EoL management.

Figure 14 shows a heat map of expected PV waste in Europe. Besides Germany, most PV is located in the above mentioned southern European countries, which is what would be expected as the radiation levels, and therefore solar panel output is significantly higher closer to the equator.

> **Geographical centre of gravity**
>
> To minimize transportation costs, the geographical centre of gravity of PV waste should be taken into account when choosing the 'ideal' locations for recycling plants in Europe.

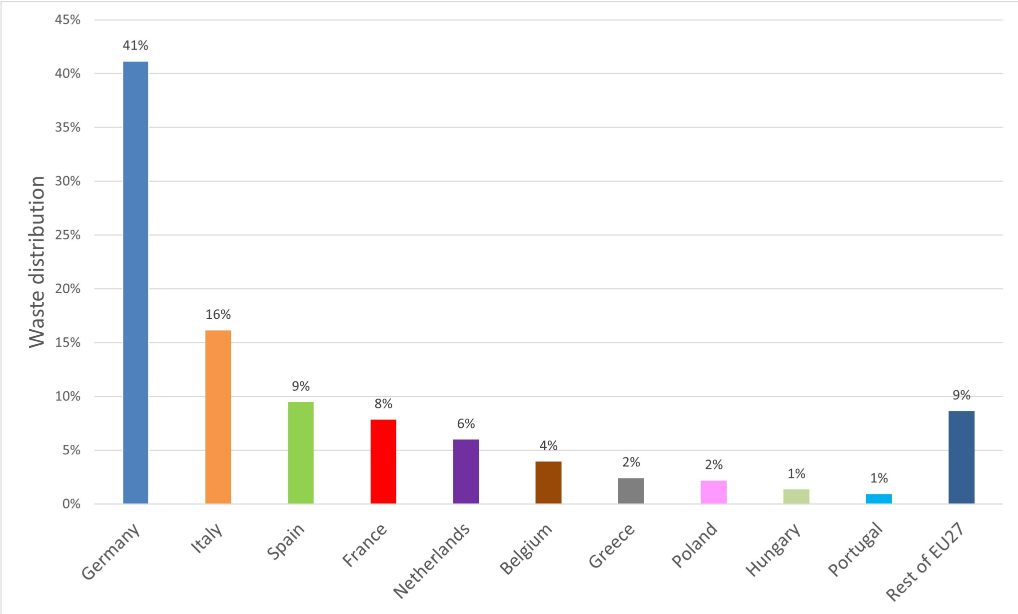


Figure 13: Waste distribution between 2020-2050.

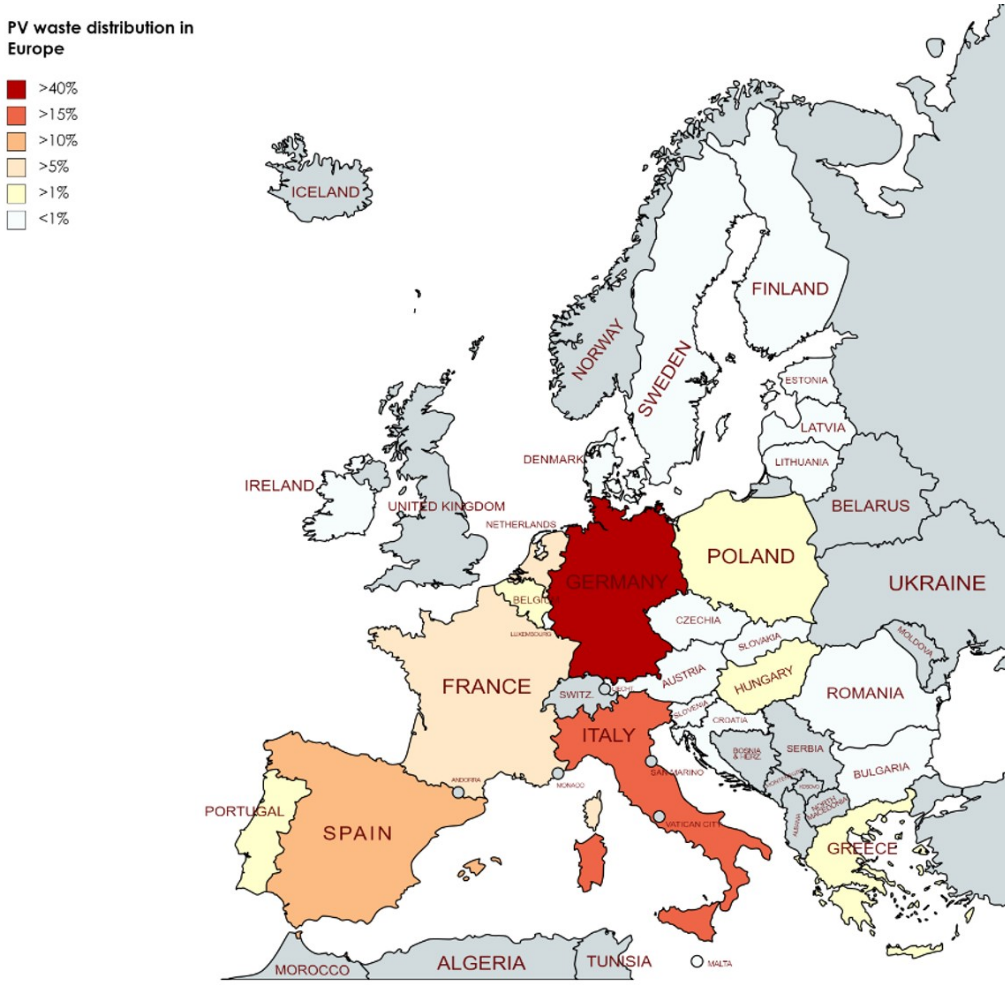


Figure 14: Heat map of PV waste distribution created at mapchart.net.

5.2.2 Country specific annual waste volumes

Figure 15 shows the annual waste volume of the ten biggest PV industries in Europe. Annual PV waste grows in all countries in the moderate and strong PV penetration scenarios. In the business-as-usual scenario, however, annual PV waste declines in later years in Germany, Italy, France, Belgium and Greece. In case of the business-as-usual scenario the overall recycling capacity in these countries would eventually need to be scaled down again.

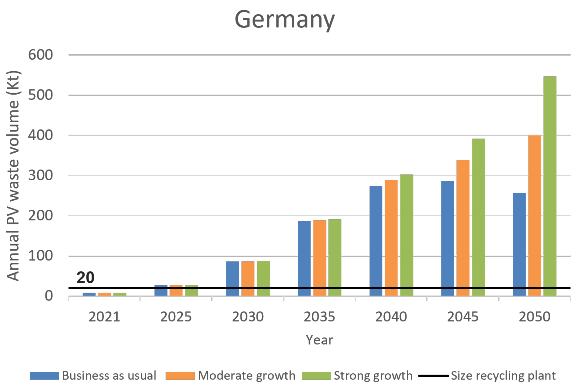
Reaching the necessary capacity for recycling

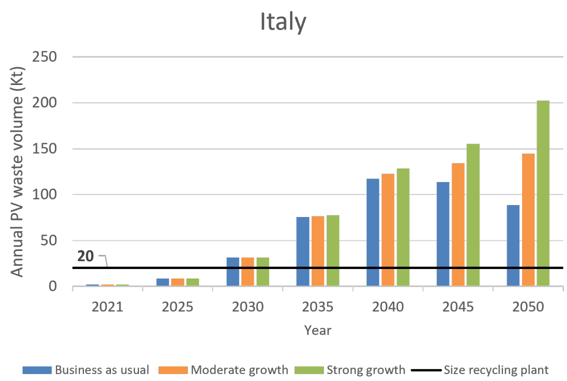
The black line in each of the graphs, shown in figure 15, indicates the size of a commercial FRELP recycling plant. As discussed in chapter 2.3, a FRELP recycling plant needs to process approximately 20 kt of PV waste per year, for it to become commercially viable. When the black line intersects with a waste volume scenario in a certain year, theoretically, the country produces enough PV waste to run a FRELP facility at full capacity.

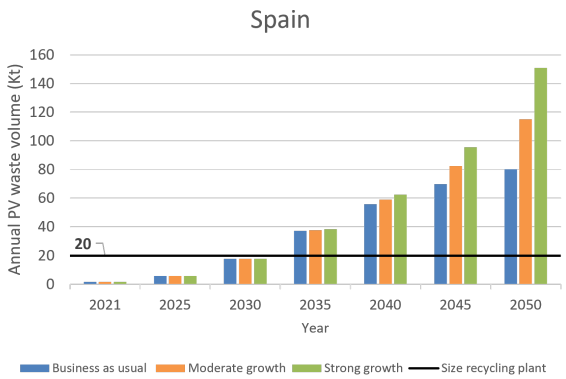
As can be seen in figure 15, none of the ten biggest PV industries in Europe are expected to produce 20 kt of PV waste in 2021. From 2025 onwards Germany's waste volume is potentially large enough to run a recycling facility at 20 kt/y, assuming that all PV waste is collected. As currently approximately only 50 percent of the waste is collected, this might be a little optimistic. Most countries will not generate enough waste to run a facility like this the coming decades. Portugal will not even produce high enough waste volumes in 2050 to process 20 kt/y, let alone the other member states with even smaller PV markets.

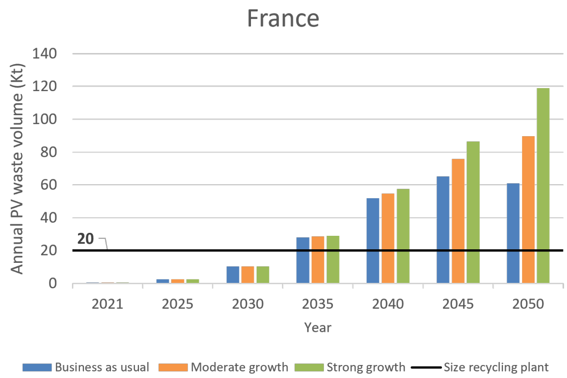
Centralized recycling

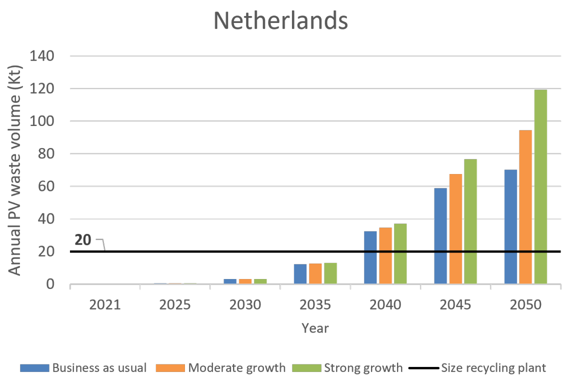
To solve the capacity issue, countries could cooperate and bundle their PV waste. This will become less important as the amount of annual PV waste increases over the years and enough waste is collected to successfully operate multiple recycling facilities.

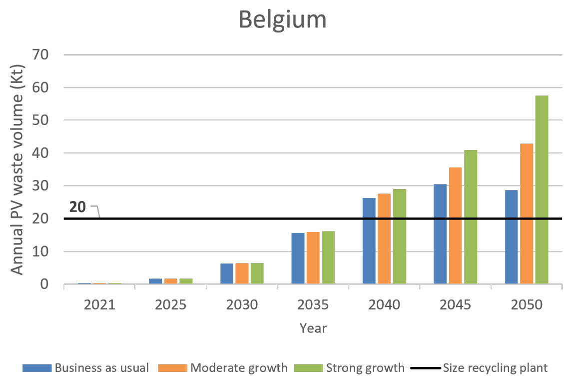

Germany
Annual PV waste volume (Kt)
600
500
400
300
200
100
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant


Italy
Annual PV waste volume (Kt)
250
200
150
100
50
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant


Spain
Annual PV waste volume (Kt)
160
140
120
100
80
60
40
20
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant


France
Annual PV waste volume (Kt)
140
120
100
80
60
40
20
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant


Netherlands
Annual PV waste volume (Kt)
140
120
100
80
60
40
20
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant


Belgium
Annual PV waste volume (Kt)
70
60
50
40
30
20
10
0
20
2021 2025 2030 2035 2040 2045 2050
Year
Business as usual
Moderate growth
Strong growth
Size recycling plant

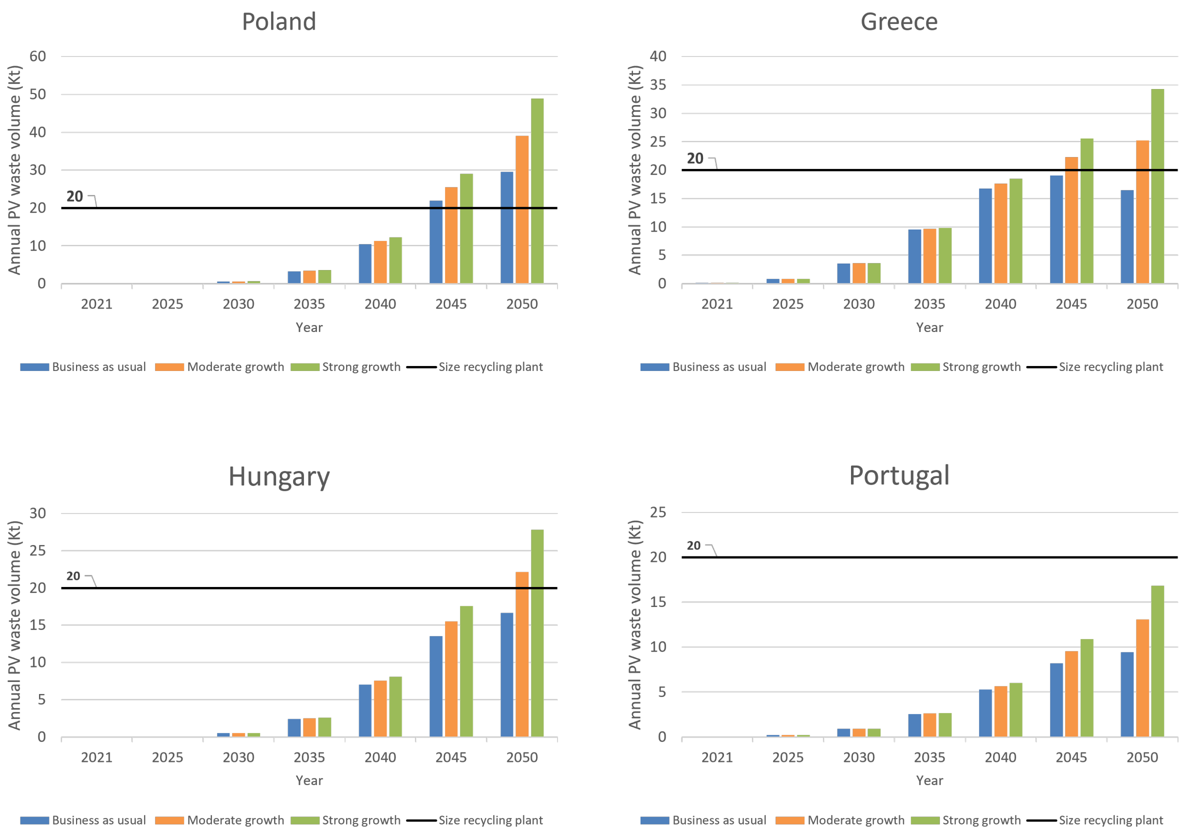


Figure 15: Calculated annual PV waste volume of the ten biggest PV markets in Europe.

5.2.3 Cumulative PV waste in Europe

To get a better understanding of the magnitude of the PV waste issue that is developing in Europe, table 5 provides an overview of the cumulative waste volumes expected in individual countries and Europe as a whole, between 2021-2050.

Table 5: Cumulative expected PV waste volumes in EU member states.

	Business-as-usual [Mt]	**Moderate growth** [Mt]	**Strong growth** [Mt]
Total	12.4	14.2	16.1
Germany	5.09	5.82	6.56
Italy	2.00	2.29	2.58
Spain	1.17	1.35	1.53
France	0.978	1.12	1.27
Netherlands	0.748	0.870	0.996
Belgium	0.490	0.562	0.635
Greece	0.300	0.344	0.390
Poland	0.269	0.317	0.367
Hungary	0.168	0.196	0.224
Portugal	0.114	0.133	0.152
Rest of EU27	1.07	1.23	1.40

Depending on the scenario, the total amount of waste is projected to be between 12-16 Mt in 2050. The cumulative waste estimates show that processing and recycling all decommissioned PV modules will be a significant challenge in the coming decades. To effectively manage the high volumes of decommissioned panels and ensure that most of the materials contained in the PV waste are reused in the future, a well-coordinated recycling effort is needed in Europe.

5.3 Material streams

The previous paragraphs focused on the volumes of future PV waste. To eventually be able to calculate the value of the emerging PV waste, this subsection will briefly discuss the material makeup of the expected waste streams.

Material make up

The mass share of the various materials is shown in figure 16. The PV waste stream predominantly consists of glass and aluminium. As much as 88.5 percent of the total weight of the PV waste comes from the glass sheet and aluminium frame. Silicon only contributes for approximately 3.7 percent of the total mass. This is due to the fact that the silicon wafers inside the solar panels are very thin, 160 µm thick on average. Until a certain degree, thin wafers are more efficient in generating electricity and also cheaper to produce. The remaining waste consists of various plastics (EVA, PVF and PVC) and metals (copper, silver, lead and tin).

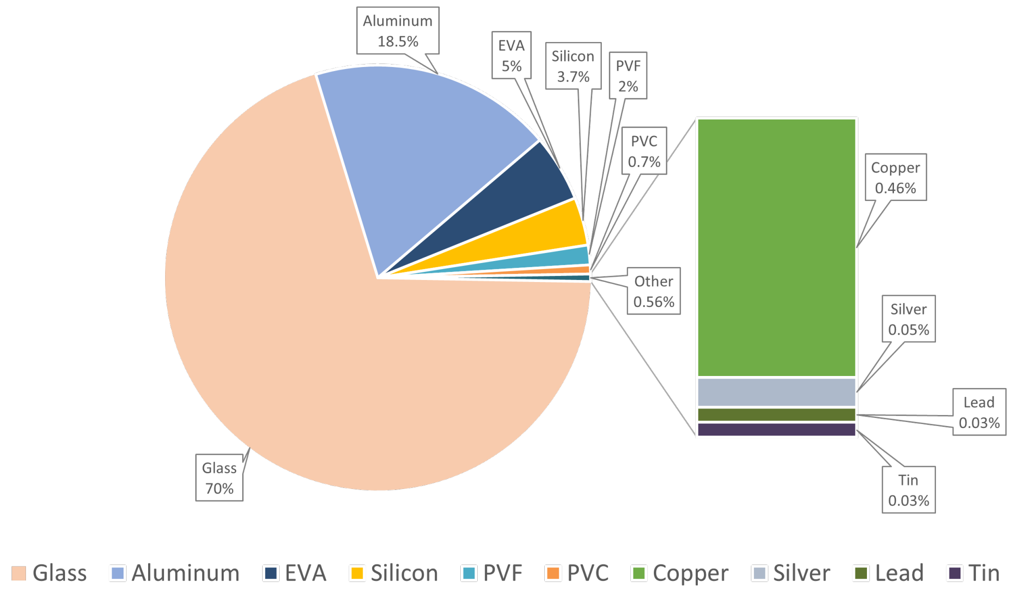


Figure 16: Average mass share and material composition of c-Si PV waste.

Cumulative material streams

Table 6 shows a breakdown of the total mass of the various materials in the cumulative PV waste volume between 2021-2050 in Europe, for the three solar penetration scenarios. The cumulative PV waste contains significant amounts of glass, various valuable metals and plastics. If Europe manages to process and reuse these materials, they could be used as raw materials in numerous industries, creating significant value. Some of the industries in which the recycled materials could play a role, will be discussed in more detail in chapter 9. The potential value of the recycled materials will be analysed in the next chapter.

Table 6: Cumulative PV material streams for all scenarios.

	Business-as-usual [Mt]	**Moderate growth** [Mt]	**Strong growth** [Mt]
Total	12.4	14.2	16.1
Glass	8.69	9.96	11.3
Aluminium	2.30	2.63	2.98
EVA	0.633	0.730	0.821
Silicon	0.453	0.520	0.588
PVF	0.186	0.214	0.242
PVC	0.0848	0.0972	0.110
Copper	0.0572	0.0656	0.0742
Silver	0.006 58	0.007 55	0.008 53
Lead	0.003 29	0.003 77	0.004 27
Tin	0.003 29	0.003 77	0.004 27

5.4 Sub-question 2: Waste volumes and material streams

In this section future PV waste volumes for Europe as a whole and its individual member states were analysed, answering the following sub-question:

> *What PV waste volumes and material streams can be expected in Europe up until 2050?*

In the coming years, **annual PV waste** is predicted to grow significantly. However, the waste streams expected in Europe up until 2050 vary depending on the future PV market share scenarios. Although, in the first decades, the annual PV waste flow is expected to be quite similar among the three scenarios, after 2040, they start to deviate considerably. In 2050, the annual PV waste in the strong growth scenario (1,450 kt) is almost double the annual PV waste expected in the business-as-usual scenario (720 kt).

The amount of PV waste in Europe is rather **unequally distributed** among member states. Germany will lead waste generation the coming decades, with more than 40 percent of the waste market share between 2021-2050. While Germany will experience a significant challenge to deal with the enormous amounts of PV waste, other member states such as Portugal will probably struggle to collect enough waste to successfully run their own PV recycling plant.

It is expected that the **cumulative PV waste** from 2021 until 2050 will range somewhere between 12-16 Mt, depending on future installed capacity. The bulk of the material stream consists of glass and aluminium, while the remaining waste is made-up of various plastics and valuable or toxic metals. The enormous amounts of expected waste confirm the importance of establishing an effective PV EoL management system in Europe.

6 The economic potential of future PV recycling

In this chapter the economic potential of the future PV market will be analysed. The aim of this chapter is to provide a better understanding of the PV waste market value and in what scenarios a profitable industry might emerge.

First the value of the waste stream is investigated. Next, current and possible future recycling costs are estimated. Eventually, by comparing the material value (€/t) and the estimated total recycling costs (€/t), the possibility of a profitable recycling industry in the future is examined.

6.1 Material value

The value of the PV waste stream is discussed in this paragraph. First, the value of one tonne of PV waste is estimated, followed by an analysis of the annual and cumulative value of Europe's PV waste market as a whole, providing an answer to sub-question 3:

> **Sub-question 3:** What is the estimated value of the PV waste stream?

6.1.1 Value of a tonne of PV waste

The material value of the PV waste is calculated for both recycling yield scenarios. Table 7 shows the total material value of a tonne of PV waste based on the recycling yields obtained in the baseline recycling process. Table 8 shows the value of a tonne of PV waste based on the FRELP recycling process.

Based on current scrap material prices the value of the recovered material of a tonne of PV waste, in the **baseline recycling process**, is estimated to be € 287. However, taking a 20 percent price fluctuation into account, this could range between € 230 and € 345.

The value of recovered material using the **FRELP recycling process** is significantly more and is estimated to be € 650, taking into account price fluctuations this could range from € 520 to € 780.

Table 7: Value of recovered material of one tonne of PV waste based on the yields of the **baseline recycling process**.

	Material mass [kg]	**Recycling yield**	**Commodity price [€/kg]**	**Material value [€]**	**Economic value share [%]**
Total	1000	N.A.	N.A.	287	100
Aluminium	185	0.994	1.19	218.4	76.1
Glass	700	0.98	0.10	68.6	23.9

Table 8: Value of recovered material of one tonne of PV waste based on the yields of the **FRELP recycling process**.

	Material mass [kg]	**Recycling yield**	**Commodity price [€/kg]**	**Material value [€]**	**Economic value share [%]**
Total	1000	N.A.	N.A.	650	100
Silver	0.53	0.94	561.25	279.6	43
Aluminum	185	0.994	1.19	218.4	33.6
Glass	700	0.98	0.10	68.6	10.6
Silicon	36.5	0.97	1.87	66.3	10.2
Copper	4.61	0.97	3.81	17.1	2.6

The bar chart in figure 17, visualizes the total value of the materials recovered from one tonne of PV waste and the value share of the materials, for both the baseline and FRELP recycling process. Using the FRELP process, significant value can be gained due to the recycling of silicon, copper and especially silver.

With 76.1 percent of the value share, aluminium is by far the number one value driver in current recycling processes. In the FRELP process, aluminium is still an important part of the total material value, however, silver is the main value driver. Extracting silver accounts for 43 percent of the total material value when PV waste is processed using FRELP recycling technology.

Extracting silver

Silver is rather difficult to extract from the solar modules, as it is ingrained in the silicon wafer. The recovery of silver considerably increases the economic value of PV waste, however, currently it is also the most expensive part of the FRELP recycling process. It would be interesting to invest in R&D focused on cost effective extracting of silver from PV modules, to minimize recycling costs while increasing the value of the waste streams.

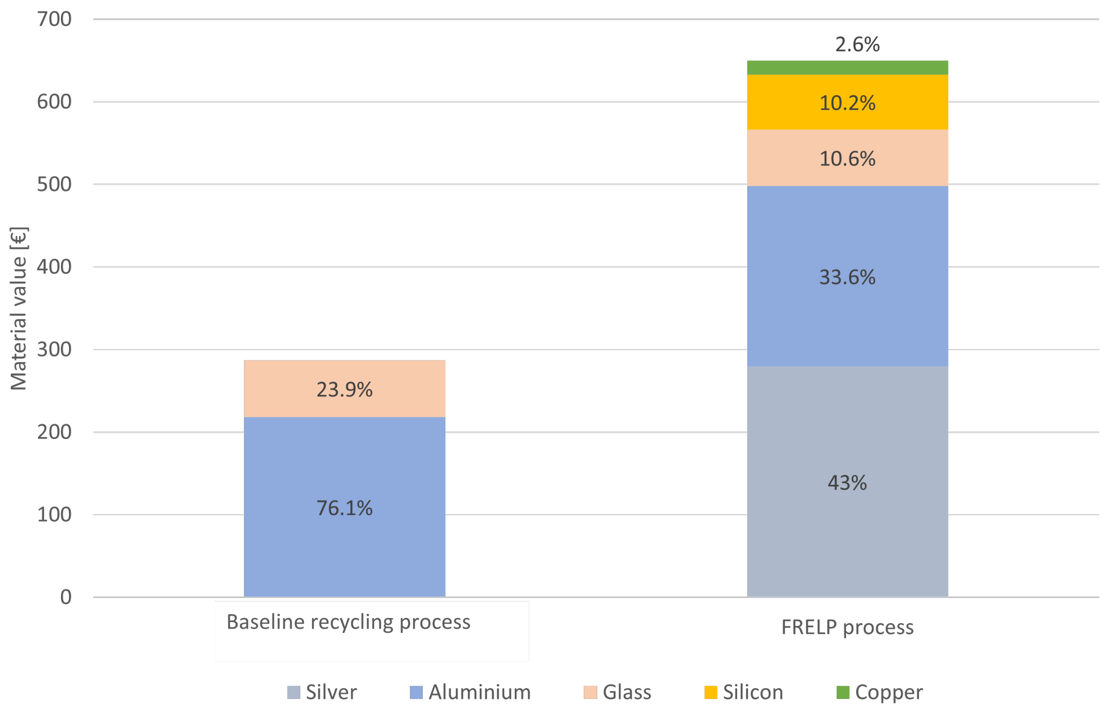


Figure 17: The value (€) of the materials recovered from one tonne of PV waste and material value share (%) of the baseline recycling process and the FRELP recycling process.

6.1.2 Annual and cumulative market value

In this subsection estimations are done for the potential annual and cumulative market value. The estimations are based on the waste volume predictions, current material scrap prices and the recycling yields of both the baseline recycling process and the FRELP process.

Annual value

Figure 18 shows the potential annual PV waste market value. The market value is expected to grow significantly from 2021 up until 2050. The annual market value in 2050 could be more than 50 to a 100 times as large as the annual market value in 2021, depending on the PV penetration scenario.

Based on FRELP recycling yields, the market could reach an annual value between 470 M€[2] and 940 M€, depending on future installed capacity. This is more than double the value than could be achieved with the baseline recycling process.

As the market grows, more and more potential value is lost when Europe continues to neglect recycling some of the most valuable materials in the PV waste stream. In 2050, the annual value that could be gained by recycling in FRELP recycling plants instead of general purpose facilities ranges between 260 M€ in the business-as-usual scenario to 530 M€ in the strong growth scenario.

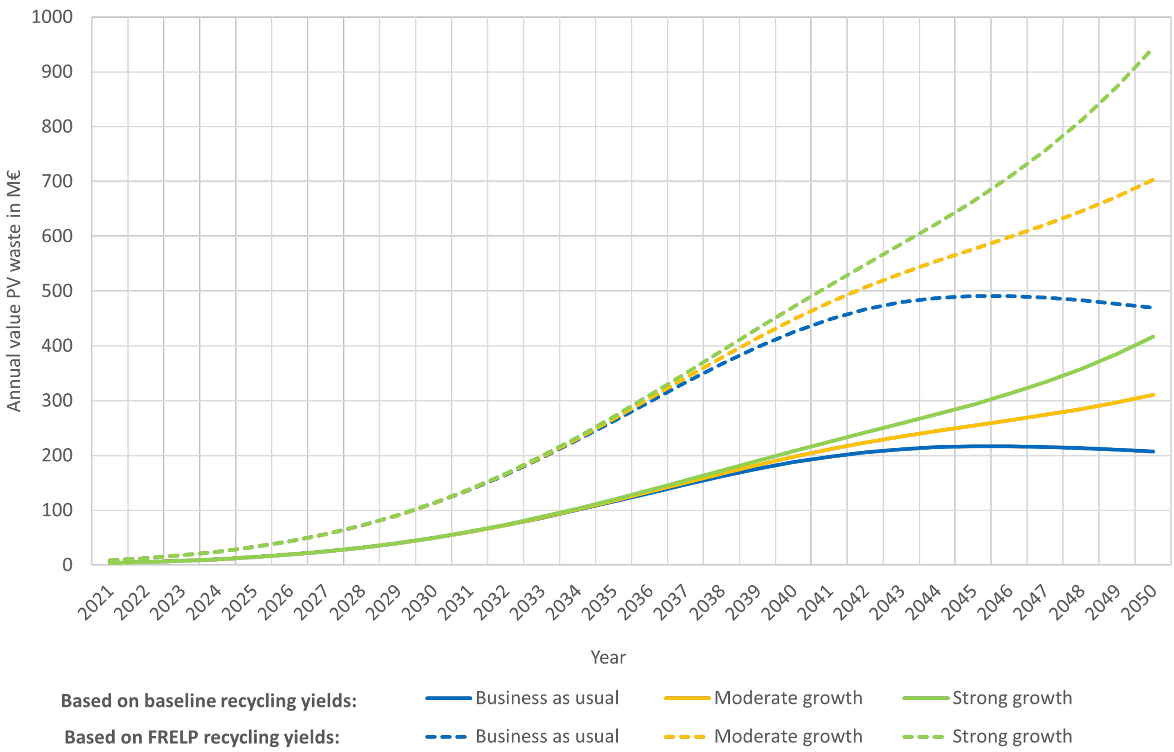


Figure 18: Expected annual value of Europe's PV recycling market.

[2] 470 M€= € 470·10^6

Cumulative value

Figure 19 shows the cumulative market value for all PV waste expected between 2021 and 2050. For the baseline recycling process, this ranges between 3.5 G€[3] and 4.6 G€, while the potential cumulative value based on the FRELP process ranges between 8 G€ and 10.5 G€. Even if the recycling yields of the FRELP process are not fully obtained, a modest increase in the yield of silver can already increase the cumulative market value significantly.

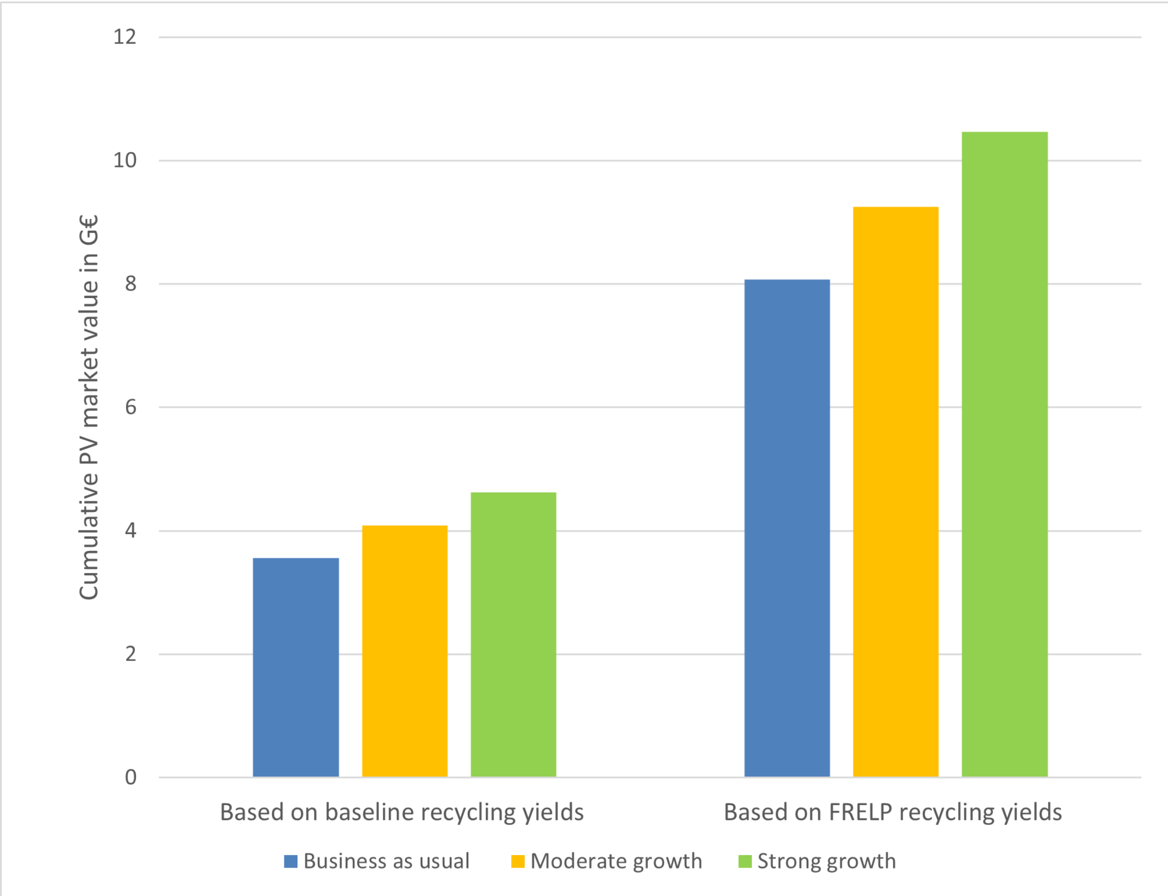


Figure 19: The cumulative PV waste market value from 2021-2050 for multiple scenarios.

Two things have to be noted:

First, many of the current general purpose recycling facilities are not able to recover the glass at a high purity level. Therefore, the total value based on current recycling practices is likely to be even less than calculated for the baseline recycling scenario.

Second, the potential market value is based on the total waste stream, collection rates have not been taken into account in this particular calculation.

[3] 3.5 G\$ = \$ $3.5 \cdot 10^9$

6.1.3 Sub-question 3: Material value

In this section the value of the recovered PV materials was analysed, answering the following sub-question:

What is the estimated value of the PV waste stream?

Based on current recycling practices **the value of a tonne of PV waste** is approximately 287 €/t, while based on the FRELP recycling process the value of a tonne of PV waste is estimated to be € 650. It is important to note that the value in the future could differ due to fluctuating material commodity prices.

As waste streams continue to grow, a significant increase in annual **market value** is expected in the coming decades. Based on the FRELP recycling yields the cumulative value of all PV waste expected between 2021-2050 ranges between 8 G€ and 10.5 G€, depending on future installed capacity. However, this is based on the total waste volume, currently only about 50 percent of all waste is collected. In order to reap the benefits of this growing market PV waste collection rates need to be increased.

6.2 Recycling costs

In this subsection the recycling costs of PV waste (€/t) are estimated. As discussed in more detail in chapter 4, the recycling costs are divided into disassembling, transportation and recycling process costs. Since the costs are influenced by the amount of annual PV waste, the total costs are analysed for all three waste stream scenarios. The analysis starts from the year 2023, as this is the first year enough annual waste is expected (roughly 28 kt/y) to run a FRELP recycling facility at a capacity of 20 kt/y. This section provides an answer to the following sub-question:

> **Sub-question 4:** What are the estimated future costs of PV recycling?

6.2.1 Disassembling costs

Figure 20 shows the estimated decrease in disassembling costs over the years, for all PV penetration scenarios and cost reduction patterns.

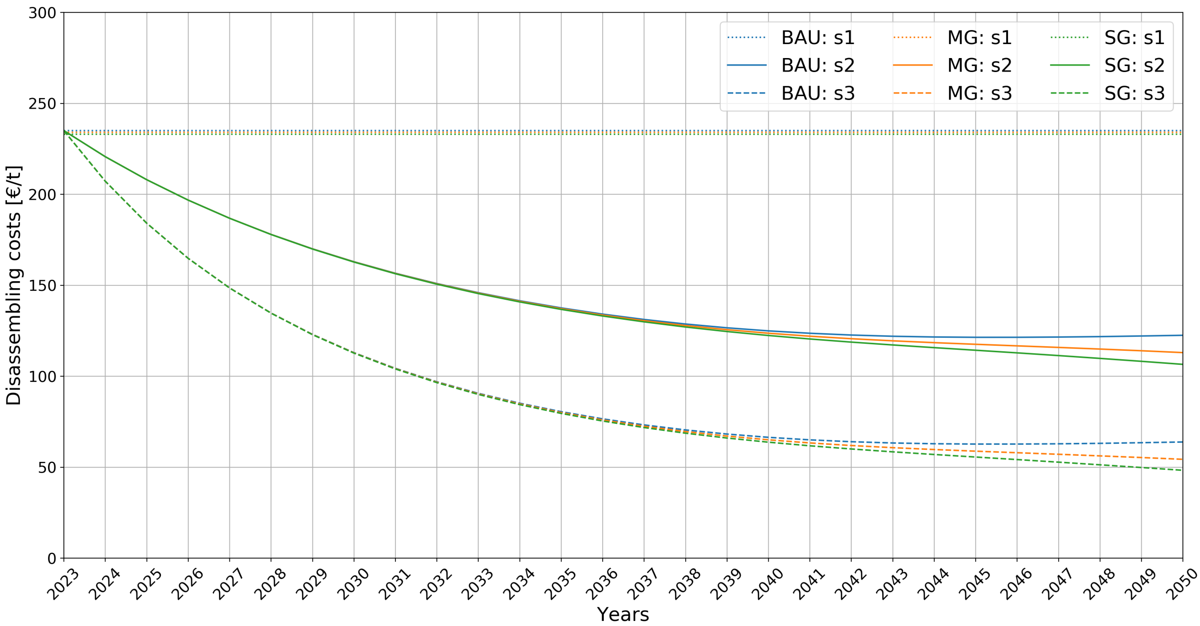


Figure 20: The disassembling costs reduction curve for all three PV penetration scenarios (business-as-usual (BUA), moderate growth (MG) strong growth (SG)) and process cost reduction patterns (weak decline (s1), average decline (s2) and strong decline (s3) in costs).

Currently the disassembling costs are estimated to be roughly 235 €/t.

- In the **weak decline** in cost scenario the disassembling costs are not affected by the increasing market size and stay the same for all three PV penetration scenarios.
- In the **average decline** in cost scenario the disassembling costs decrease with approximately 50 percent to roughly 120 €/t in 2050.
- In the **strong decline** in cost scenario the disassembling costs could decrease with more than 80 percent to about 50 €/t in 2050.

Figure 20, shows that there is only a small difference between the various PV penetration scenarios with the same cost reduction pattern (scaling factor). This difference only starts to become apparent after the year 2035. This is due to the fact that the PV penetration scenarios generate similar amounts of annual waste up until this year. After 2035, the PV penetration scenarios start to deviate which can also be seen in the graph. However, as waste volumes are already substantial in 2035, the difference between the three PV penetration scenarios has a relatively minor effect on the average disassembling costs.

To conclude, the biggest differences between the cost reduction curves are caused by the scaling factors used in the cost reduction scenarios and not by the amount of PV waste.

6.2.2 Transportation costs

To estimate future transport costs two scenarios were investigated, a scenario 'without pre-treatment' and a scenario 'with pre-treatment'.

Costs in case of one FRELP facility

The first FRELP recycling facility is assumed to be located in the centre of Germany near Eisenach, as this is roughly the geographic central point of gravity of PV waste in Europe. The average distance from a PV plant or collection point in Europe to this recycling facility is estimated to be about 660 km.

Scenario without pre-treatment ($C_{t\ WOT}$)

The average cost of transportation from a PV plant to the recycling facility, in a scenario without pre-treatment and only one PV recycling plant in Europe, is approximately 240 €/t.

Scenario with decentralized pre-treatment ($C_{t\ WT}$)

In the transportation scenario with pre-treatment the total average distance is higher than in a scenario without pre-treatment (100 km + 660 km). However, pre-treating the waste with the first step of the FRELP recycling process, decreases the weight of the PV waste with 88.5 percent (18.5 percent for the aluminium frame, and 70 percent for the glass shield). After pre-treatment one tonne of PV waste is reduced to only 115 kg.

As described in chapter 4, the transportation costs are linearly correlated with the weight of the material. Therefore, what would initially be 240 €/t for the transportation from the collection point to the recycling facility, is reduced to 28 €/t with pre-treatment.

The total transportation cost in a scenario with pre-treatment in case of one recycling facility is 64 €/t. This is the sum of 36.6 €/t for transportation costs from a PV plant to a collection point (see chapter 4.2.2 for the calculation), plus 28 €/t for transportation costs from a collection point to the recycling facility. This is significant cost improvement (see figure 21).

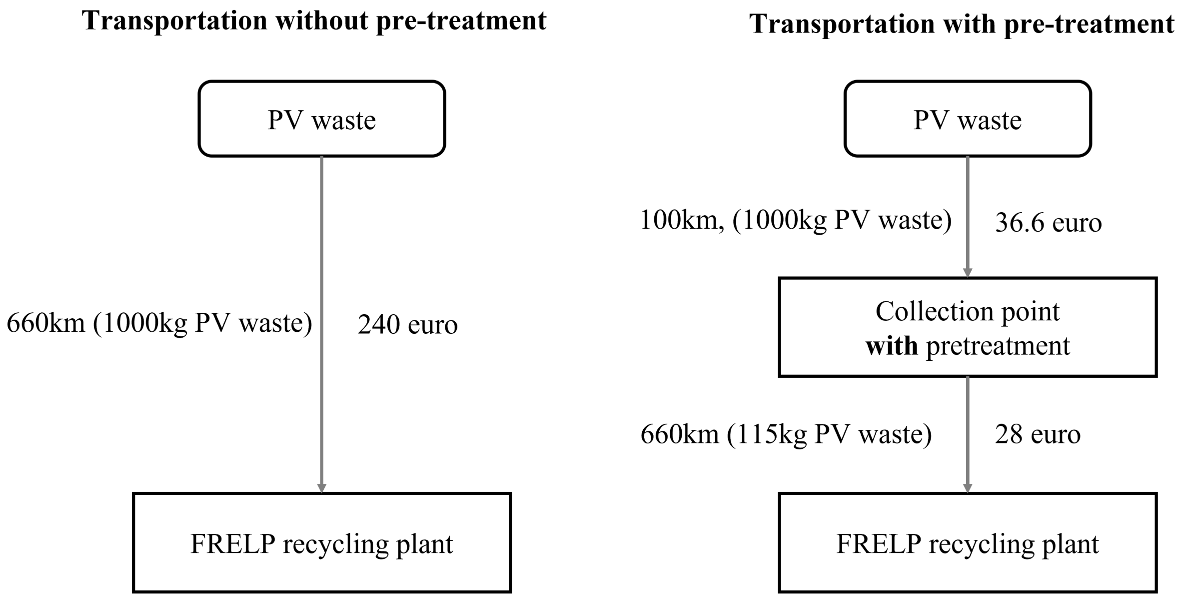


Figure 21: Transportation costs of 1 tonne of PV waste in a scenario without pre-treatment and a scenario with pre-treatment, in case of only one operating FRELP recycling facility in Europe.

Comparing the transportation scenarios over the years

Table 9, 10 and 11, provide an estimation of average future transportation costs for all three PV penetration scenarios, for both transportation with and without pre-treatment. The transportation costs decline as the number of PV recycling facilities increase, due to the growth in annual PV waste volume.

As waste streams are similar for the three PV penetration scenarios in the first decades, the costs of transportation, are expected to be almost identical for the scenarios in these years. Although the yearly waste volumes start to deviate quite strongly after 2045, the estimated transportation costs do not differ significantly. This is due to the fact that extra recycling facilities added in later years, when there are already numerous facilities in operation, have less of an effect on the decrease in average transportation distance.

Pre-treatment also the winning strategy over the years

Transportation with pre-treatment is the **cheapest option** in every year for every scenario. However, the difference is most apparent in the first decades as recycling plants are limited in these years, and therefore average transportation distances are high. The advantage of the pre-treatment scenario reduces over the years, as more recycling facilities are added to the recycling network in Europe.

The largest part of the transportation costs in the scenario with pre-treatment comes from the transportation from the PV plant to the collection point. Although not taken into account in the model, as the waste volumes grow, potentially more **collection points** become available. This would decrease the distance from PV plants to the collection points and therewith decrease the costs of the pre-treatment scenario even more. It might be the case that eventually, when large numbers of PV recycling facilities are operating throughout Europe, collection points for pre-treatment become ineffective as the distance to a recycling facility become negligible.

Actual economic feasibility

Pre-treatment is seen as a technological possibility according to the inventors of the FRELP recycling process (Ardente et al., 2019). However, the economic feasibility of decentralized pre-treatment is dependent on the volume of waste that is accumulated at the local collection points (Ardente et al., 2019). If waste volumes are too low, pre-treatment might increase overall recycling process costs.

However, the data necessary to calculate this is currently not available, but as long as the transportation cost benefit of pre-treatment is more than the potential extra process costs, this seems to be a solid strategy for the future. Besides possible cost reduction, this strategy could also drastically decrease the carbon emissions of transportation, as significantly less material weight would have to be transported over large distances.

Table 9: Transportation costs in the business-as-usual scenario.

	2023	2025	2030	2035	2040	2045	2050
Expected waste [kt]	28	51	173	404	655	756	722
FRELP facilities (20 kt/y)	1	2	7	17	27	32	30
Average distance [km]*	(+100) 656	(+100) 574	(+100) 306	(+100) 205	(+100) 156	(+100) 150	(+100) 153
$C_{t\ WOT}$ [€/t]	240	210	112	75	57	55	56
$C_{t\ WT}$ [€/t] **	64	61	50	45	43	43	43

Table 10: Transportation costs in the moderate growth scenario.

	2023	2025	2030	2035	2040	2045	2050
Expected waste [kt]	28	51	174	410	690	888	1,081
FRELP facilities (20 kt/y)	1	2	7	17	29	37	45
Average distance [km]*	(+100) 656	(+100) 574	(+100) 306	(+100) 205	(+100) 153	(+100) 142	(+100) 134
$C_{t\ WOT}$ [€/t]	240	210	112	75	56	52	49
$C_{t\ WT}$ [€/t]**	64	61	50	45	43	43	42

Table 11: Transportation costs in the strong growth scenario.

	2023	2025	2030	2035	2040	2045	2050
Expected waste [kt]	28	51	174	417	725	1,022	1,453
FRELP facilities (20 kt/y)	1	2	7	17	30	43	61
Average distance [km]*	(+100) 656	(100) 574	(+100) 306	(+100) 205	(+100) 153	(+100) 137	(+100) 112
$C_{t\ WOT}$ [€/t]	240	210	112	75	56	50	41
$C_{t\ WT}$ [€/t]**	64	61	50	45	43	42	41

**The average distance of transportation with pre-treatment is an extra 100km covering the distance from the PV plant to the collection point.*

*** The values are a sum of the fixed transportation costs from PV plant to collection point (36.6 €/t) and the variable transportation costs from collection point to the recycling facility.*

6.2.3 FRELP process costs

As described in the chapter 4, current average FRELP process costs are estimated to be around 461 €/t (Ramon, 2021). Figure 22 shows the expected decrease in FRELP recycling process costs over the years for all waste stream scenarios and cost reduction patterns, as a result of economies of scale.

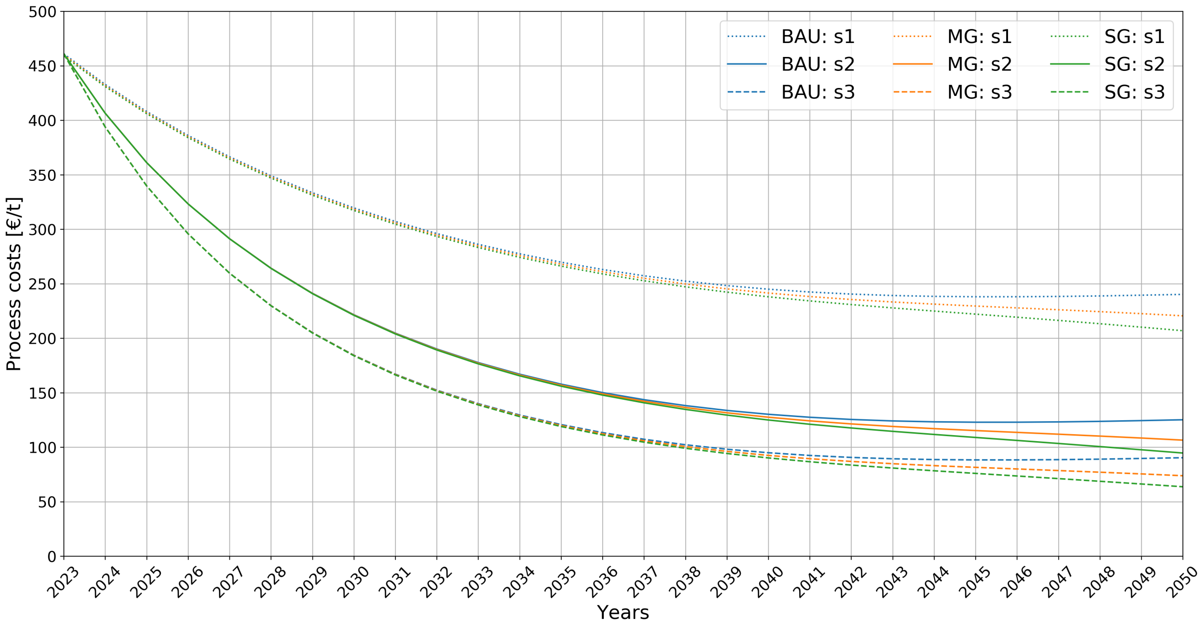


Figure 22: The process cost reduction curve for all three PV penetration scenarios (business-as-usual (BUA), moderate growth (MG) strong growth (SG)) and process cost reduction patterns (weak decline (s1), average decline (s2) and strong decline (s3) in costs).

As expected, due to lower scaling factors, the scaling effects in the various scenarios are stronger for the process costs than for the disassembling costs. The decrease in process cost in 2050 range between 48 percent, with a weak scaling effect, in the business-as-usual scenario and about 87 percent, in case of a strong scaling effect in the strong growth scenario. Even with a modest scaling factor the average process costs are likely to decline significantly.

Similar to disassembling costs, the process cost reduction is mainly influenced by the scaling factor (weak, average and fast cost reduction) up until 2035. Only after that year the various PV penetration scenarios start to have an effect on the average FRELP process costs.

6.2.4 Total costs

The total costs of recycling a tonne of PV waste (C_{tot}) were calculated by adding together the estimated disassembling (C_d), transportation (C_t) and process costs (C_p) of a given year.

There seems to be a negligible difference between the expected total recycling costs for the three PV penetration scenarios (business-as-usual, moderate growth and strong growth) up until 2040. After 2040, differences between the PV penetration scenarios start to become more apparent. However, the first decades are actually more interesting to us, since the reliability of forecasts decrease as the time span increases. Therefore, for simplicity, the total costs over the coming decades will only be shown for one scenario.

The business-as-usual scenario is chosen, as this is the most conservative scenario of the three. Table 12 and 13, provide a breakdown of the various costs for the coming years in a scenario with or without pre-treatment. Both tables show the total costs in case of a weak (s1), average (s2) and strong (s3) decline in disassembling and recycling process costs.

Due to increasing waste streams over the coming decades, a considerable decline in costs is expected for the PV recycling industry. Only between 2045 and 2050, a slight increase in costs is projected. This is due to decreasing annual waste volumes in later years in the business-as-usual scenario. This would not be the case in the other, less conservative scenarios.

In the next chapter the expected annual recycling costs (€/t) will be compared to the estimated annual material value (€/t), to investigate the economic potential of the future PV recycling market.

Table 12: Total recycling costs without pre-treatment.

	2023	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Expected PV waste [kt]	28	51	173	404	655	756	722
FRELP facilities	1	2	7	17	27	32	30
C_d s1 [€/t]	235	235	235	235	235	235	235
C_d s2 [€/t]	235	208	163	138	125	121	122
C_d s3 [€/t]	235	184	113	80	66	63	64
$C_{t\ WOT}$ [€/t]	240	210	112	75	57	55	56
C_p s1 [€/t]	461	408	320	270	245	238	240
C_p s2 [€/t]	461	361	222	158	130	123	125
C_p s3 [€/t]	461	340	184	121	95	88	90
C_{tot} s1 [€/t]	936	853	667	580	537	528	531
C_{tot} s2 [€/t]	936	779	497	370	312	299	303
C_{tot} s3 [€/t]	936	734	410	276	218	206	210

Table 13: Total recycling costs with pre-treatment.

	2023	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Expected PV waste [kt]	28	51	173	404	655	756	722
FRELP facilities	1	2	7	17	27	32	30
C_d s1 [€/t]	235	235	235	235	235	235	235
C_d s2 [€/t]	235	208	163	138	125	121	122
C_d s3 [€/t]	235	184	113	80	66	63	64
$C_{t\ a}$	37	37	37	37	37	37	37
$C_{t\ b}$	28	24	13	9	7	6	6
$C_{t\ WT}$ ($C_{t\ a}$+$C_{t\ b}$) [€/t]	64	61	50	45	43	43	43
C_p s1 [€/t]	461	408	320	270	245	238	240
C_p s2 [€/t]	461	361	222	158	130	123	125
C_p s3 [€/t]	461	340	184	121	95	88	90
C_{tot} s1 [€/t]	760	704	604	550	523	516	518
C_{tot} s2 [€/t]	760	630	434	341	298	287	291
C_{tot} s3 [€/t]	760	585	347	246	204	194	197

6.2.5 Sub-question 4: Recycling costs

In this section, the PV recycling cost categories were examined in order to estimate total recycling costs, providing an answer to the following sub-question:

What are the estimated future costs of PV recycling?

The recycling costs categories taken into account in this research were: disassembling costs, transportation costs and recycling process costs. As the market grows over the years, **disassembling costs** might decrease significantly, due to economies of scale. However, as exact scaling factors are unknown, the results range from a linear relationship between costs and market size, in the weak decline in cost scenario, to a rather significant cost reduction in the strong decline in cost scenario.

Future **transportation costs** depend on whether pre-treatment is utilized or not. Especially in the first couple of years, when waste volumes are still relatively small, transportation with pre-treatment is expected to be considerably cheaper than transportation without pre-treatment. However, before implementing this strategy, it is important to further investigate the effects of pre-treatment on the average recycling process costs.

Due to economies of scale, the FRELP **process costs** are expected to decrease strongly over the years. Even with a modest scaling factor in the weak decline in cost scenario, significant process cost reduction is expected.

The **total costs** in the first year of operation of a 20 kt/y FRELP facility, are expected to be around 940 €/t in a scenario without pre-treatment, and could be as low as 760 €/t in a scenario with pre-treatment. The estimated costs for 2050 range between approximately 530 €/t and 200 €/t, depending on the transportation and cost reduction scenario (see table 12 and 13).

Although, the recycling cost estimates vary notably and should be considered as rough approximations, they show that the recycling costs will probably decrease significantly over the coming decades, even with modest scaling effects.

6.3 Economic profitability

To investigate if the PV recycling market has economic potential, in this section the value of recovered material (€/t) will be compared to the total costs of recycling (€/t). An answer will be provided to the following sub-question:

> **Sub-question 5:** Will PV recycling be profitable in the future?

In order for PV recycling to be profitable in the future, the expected revenue should exceed the total expected recycling costs (disassembling, transportation and process costs). Figure 23 depicts the estimated annual total recycling costs without pre-treatment and figure 24 shows annual recycling costs with pre-treatment. Both graphs show the recycling cost curves over time, based on a weak, average and strong decline in disassembling and process costs scenario. Each figure contains the estimated value of current recovered material and the material value in case of a 20 percent increase or 20 percent decrease in commodity prices. Based on the graphs we can estimate when the value of the recovered materials will exceed the costs of recycling of a tonne of PV waste.

Potential profitability in a scenario without pre-treatment

Figure 23 shows that, based on current material value, a recycling scenario without pre-treatment is expected to become profitable somewhere between 2026 and 2031, depending on the cost reduction scenario. In case of a 20 percent increase in material commodity prices, PV recycling could become profitable as soon as 2025.

However, in case of a 20 percent decrease in material value and a weak decline in recycling costs, the market will not be able to break even in the coming decades. This shows the dependence of the PV recycling market on future material commodity prices, indicating the vulnerability of the market.

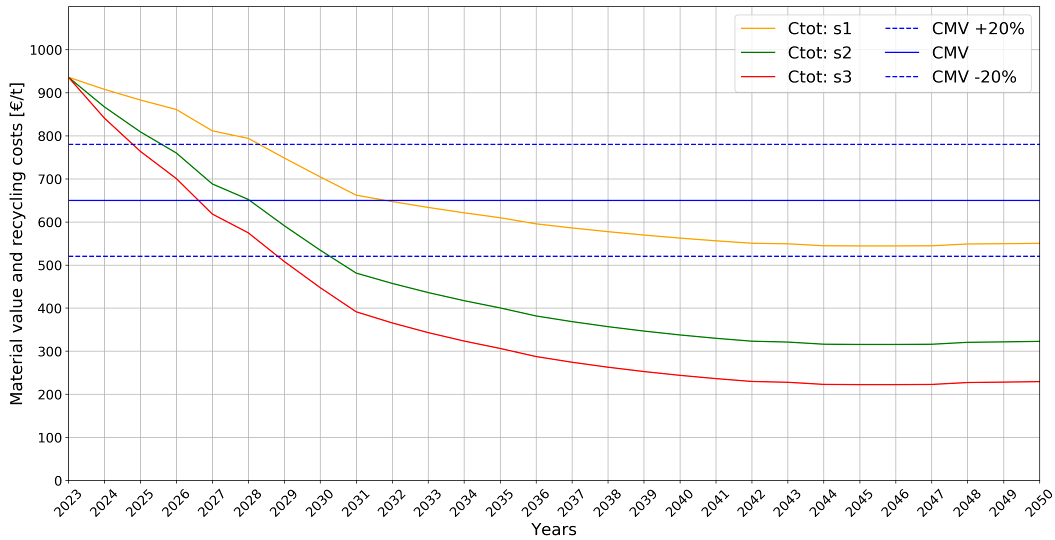


Figure 23: Total recycling cost (C_{tot}) curves (without pre-treatment) and current material value (CMV) curve.

Potential profitability in a scenario with pre-treatment

As concluded in the former section, the recycling costs with pre-treatment are expected to be lower than the costs of recycling without pre-treatment. Therefore, as can be seen in figure 24, the material value exceeds recycling costs sooner than in a scenario without pre-treatment.

In a scenario with pre-treatment, based on current material value, the recycling industry could start to become profitable between 2024 to 2027, depending on the cost reduction scenario. In case of a 20 percent increase in material value, PV recycling could be profitable from the first year in which waste volumes are expected to be high enough to run a FRELP facility with a capacity of 20 kt/y. On the other hand, if material value decreases with 20 percent and the decrease in recycling costs are weak, it could take until 2041 for the PV recycling market to break even. In this scenario the market will definitely struggle to make a profit the coming decades.

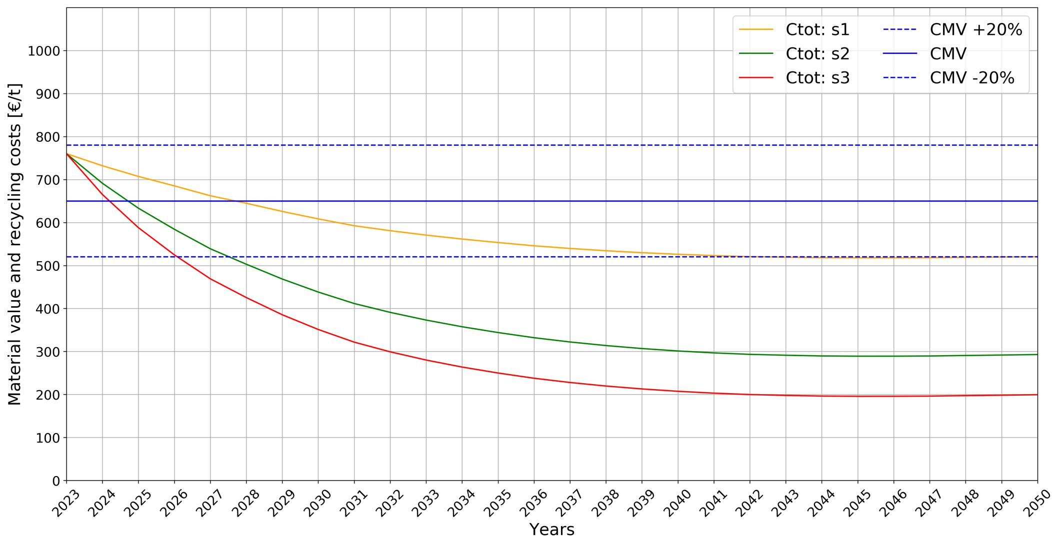


Figure 24: Total recycling cost (C_{tot}) curves (with pre-treatment) and current material value (CMV) curve.

Uncertainty affecting investment

As can be seen in figure 23 and 24, accurately determining the economic profitability in the future is rather difficult due to the uncertainty about cost reduction and material prices. Furthermore, it should be noted that simply breaking even is not a strong incentive for investment. Although it varies among industries, according to the Corporate Finance Institute, a revenue should be more than 10 percent for a company to be considered 'healthy' (CFI, 2021). An expected revenue below 10 percent is probably not seen as a solid investment. Especially in a market that dependents on fluctuating material prices to make a profit. In order for the private sector to be incentivized to start a PV recycling business, there needs to be a possibility to make a solid revenue. As illustrated in figure 23 and 24, in several scenarios a solid revenue will definitely be possible, however, in some cases this might not be achieved in the coming decades.

Covering part of the costs with subsidies

Figure 25, shows a comparison between the recycling costs without pre-treatment and with pre-treatment, in the first year of operation. The three cost categories are shown in the chart. The blue line represents the material value based on current commodity prices. Although the material value is not enough to cover total costs in any of the two scenarios, the material value should be high enough to cover the FRELP process costs. In the scenario with pre-treatment it would even cover the process costs and transportation costs. According to these calculations only the disassembling costs are not fully retrieved in the scenario with pre-treatment.

It would be ideal if all costs associated with recycling could be retrieved with the recovered material value. However, coverage of some of the cost categories would already be a step in the right direction.

In a future financial scheme where only the FRELP process costs would have to be covered by the revenue of the recycling plant and the other costs are covered by the solar panel producer or subsidies, it is likely that from the year 2023 onwards, there would be a positive business case.

Based on the scenario with pre-treatment, there might be a positive business case even if also the transportation costs have to be paid for. However, this depends on the magnitude of the potential increase in process costs due to decentralized pre-treatment. It is important to note that this is only the case if more than 85 percent of the PV waste is actually collected and recycled in the same FRELP facility.

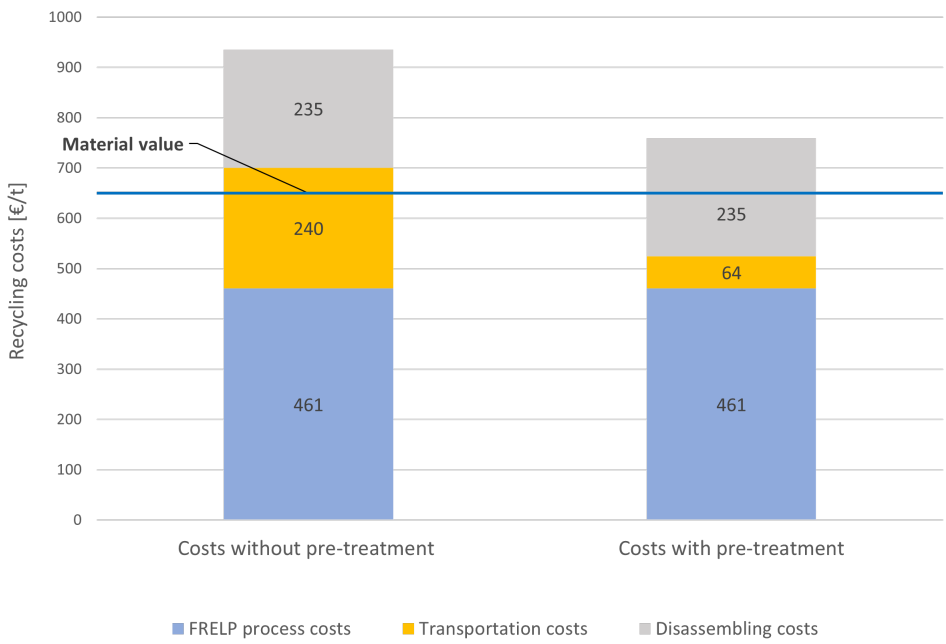


Figure 25: Estimated recycling costs (€/t) with and without pre-treatment in the first year of possible operation (20 kt/y +), compared to current material value.

6.3.1 Sub-question 5: Economic profitability

In this section, the value of the recovered PV materials (€/t) was compared to the total recycling costs (€/t), to analyse the economic potential of the PV recycling market. This provides an answer to the following sub-question:

Will PV recycling be profitable in the future?

The results show that there is definitely a possibility for a profit in the PV recycling industry in the future, but, if and when a profit is achieved, depends on:

- The cost reduction scenario
- The transportation strategy
- The material prices
- The PV collection rate (although this is assumed to be fixed in the model)

In a **favourable situation**, profitability could be achieved as soon as 2023. In this case the recycling strategy with pre-treatment needs to be utilized, material prices need to increase with 20 percent and enough waste needs to be collected to run a 20 kt/y FRELP facility at full capacity. This is unlikely to happen, especially as there is no guarantee that the material prices will increase with 20 percent.

In an **unfavourable situation**, with a weak decline in recycling costs and a 20 percent decrease in material prices, it could take decades for the PV recycling industry to ever become profitable.

Profitability with subsidies

So far the profitability was based on the notion that revenue needs to cover total costs. However, a FRELP facility run at full capacity, generates enough revenue in any scenario to cover the process costs. Moreover, in a scenario with pre-treatment it produces enough revenue to cover both process costs and transportation costs.

Therefore, if the disassembling costs are covered by a subsidy or a different party, the PV recycling industry can become profitable in 2023, when enough waste is collected to run a FRELP facility at full capacity, even in case of a 20 percent price reduction.

7 Discussion

In this section, the results are positioned in the current body of literature, the approach and methodology are reflected upon and suggestions for future research are made.

7.1 Position within the existing body of literature

Similar to previous studies carried out in different parts of the world (Domínguez & Geyer, 2017, 2019; Mahmoudi, Huda, & Behnia, 2019; Peeters et al., 2017), this waste stream assessment shows that also in Europe large PV waste volumes are expected in the coming decades. This research project adds to our understanding of the future PV recycling industry in Europe by mapping the waste streams in the individual member states. This gives us a detailed understanding of where and when a certain amount of waste can be expected in the future. This information should be taken into account when considering how to design the European PV recycling infrastructure.

Numerous studies state that recycling is currently not profitable due to small waste volumes (Mahmoudi, Huda, Alavi, et al., 2019; McDonald & Pearce, 2010; Redlinger et al., 2015). The results of this research agree, and indicate that, if you look at the total costs of the recycling process (disassembling, transportation and recycling), it is very unlikely that there will be a net economic benefit in the coming years in this market.

Redlinger et al. (2015) suggested that economies of scale might make the PV recycling industry profitable in the future. However, they do not attempt to calculate what the effects of economies of scale on recycling costs could actually be. Generally, in the PV waste forecast literature, the costs of actually retrieving the valuable materials is not really taken into account. This study contributes to the current body of literature, by modelling various cost reduction scenarios based on the increasing PV waste streams. The results suggest that even modest external economies of scale can have a great effect on recycling cost reduction and potentially make the PV recycling market a profitable industry. This knowledge can be used for policy making to, for example, determine when subsidies might be necessary to incentivize the private sector to recycle the PV waste.

Where the other literature in the PV waste forecast field is descriptive in nature, showing primarily what waste streams can be expected in future years. This study attempted to take this a step further by using a PV waste forecast to analyse possible recycling solutions and do suggestions for how to design the PV EoL infrastructure.

To conclude, the aim of this project was not only to analyse the economic potential of the PV recycling market, but also to develop a new way of thinking about PV waste streams and their effect on PV recycling costs. As long as lifetime data is available for a product, the relationship between market size and recycling costs of an industry are known, the model built for this study is generalizable. It can be used in various recycling industries to forecast waste streams and estimate future recycling costs.

7.2 Reflection on the approach and methodology

The waste stream forecast model built for this study, has proven to be useful to make rough estimations of future material streams, their value and future recycling costs. However, due to the various assumptions made, limited data and time available, the results of the model are not completely accurate or all-encompassing. Below follows a reflection on the approach and methodology used in this study.

7.2.1 Scope

Focusing only on c-Si PV recycling, allowed us to do an in-depth analysis for this particular product. However, in reality recycling organizations will often also process other panels, the junction box and they might also recycle some components of the balance of systems. As recycling some of these components might be relatively easy, changing the scope and including some of these elements could have resulted in a different, more favourable, business case.

Furthermore, an 85 percent collection rate was assumed in the model. This is relatively high, as the current collection rate is only 47 percent. It would have been interesting to do the same calculations for a scenario in which only 47 percent of the waste was collected and compare the results.

7.2.2 Data availability

As the PV recycling market is still a rather new industry, information on PV recycling costs has proven to be scarce and rather difficult to obtain. No data regarding decommissioning costs for Europe could be found. Therefore, decommissioning costs were based on a research carried out for the United States by NYSEDA (2021).

Furthermore, it is important to note that the FRELP project is still in a pilot stage. Data regarding recycling yields and recycling costs, are based on laboratory testing and estimations carried out by the developers of the FRELP process (Ardente et al., 2019; Ramon, 2021). Therefore, actual recycling yields or recycling costs might somewhat deviate from the input data.

7.2.3 Methods

Weibull distribution

There are two main drawbacks of using a continues probability distribution, like the Weibull distribution, to predict future waste streams. First, the parameters are based on current data sets. As R&D developments are unknown, future added PV capacity is assumed to have the same lifetime behaviour as current panels in the model. Expected changes to the design of c-Si solar panels in the coming decades, will cause part of the results of the waste stream assessment to be inaccurate. Fortunately, the waste volume results up until 2035 are predominantly shaped by already installed capacity, for which average panel specifications are known. Only after 2035, future added PV capacity starts to play a role in the waste stream forecast. The model and Weibull parameter values can be updated as new information becomes available.

Second, as the probability distribution smoothens out the decommissioning profile, the Weibull function does not show potential spikes and dips in decommissioning. Santos and Alonso-García (2018), expect that the irregular yearly growth of installed PV capacity in some countries could cause fluctuations in future PV waste volumes over the years. Although not apparent in the model, this could lead to recycling capacity issues and should be considered in future PV EoL management strategies. A different method for solar panel failure forecasting would need to be used to model the sudden fluctuations in decommissioning. For example, a stochastic simulation of solar panel failure could provide a solution.

Transportation cost reduction

The method used to calculate future transportation costs was useful to do cost reduction estimations. However, in real life there are numerous reasons why a facility would be opened at a certain location which are not taken into account in the model. This could very well mean that the reduction in average transportation distance is less than the 'maximum' calculated in the model. If more time was available it would have been interesting to investigate the actual 'best' locations for PV recycling facilities in Europe based on a range of criteria (e.g. the geographical gravitity of PV waste distribution, real estate costs, transportation accessibility etc.).

Scaling law

When starting the study, it was initially unknown that no scaling factors in the PV recycling industry were available. As a solution, the scaling effects of the disassembling and process costs are based on scaling factors from related industries. Although, the three cost scenarios used in the model cover a wide variety of possibilities, allowing us to prepare for various potential future realities, the scaling factors used in the scenarios are speculative at best.

In the future, by analysing the relationship between the increasing market size and cost reduction in the PV recycling industry, more accurate scaling factors can be calculated, which could be used to update the model.

Additional probability analysis

The results show the outcome regarding economic potential based on various waste stream, economic value and recycling cost reduction scenarios. However, if more time was available this could have been taken a step further by determining the actual probability of each scenario becoming reality. It would have been interesting to add a Monte Carlo analysis and see what scenarios are most likely to materialize.

7.3 Suggestions for future research

PV recycling is a rather new field of study and there are still numerous opportunities for future research. In light of the findings and limitations of this study the following suggestions for future research are made:

- First, as discussed in section 7.2.3, the Weibull distribution might not show potential spikes and dips in decommissioning, as the probability distribution smoothens out the decommissioning profile. Further research is needed to figure out if these spikes and dips actually occur in reality.
- Second, based on the results of the model, pre-treatment seems to be a solid strategy to reduce transportation costs. However, the effects of pre-treatment on overall process costs are still unknown. Therefore, it would be valuable if future research further investigated the pre-treatment scenario to see if the transportation cost advantages out way the potential increase in process costs.
- Third, finding the best locations for PV recycling plants throughout Europe could be an interesting topic for future research. The waste stream data from this study could be used to find the geographic central points of gravity. These could be taken into account when identifying PV recycling locations.
- Fourth, this study showed that economies of scale could have a significant effect on PV recycling costs. Future research should investigate how government policy could stimulate external economies of scale in the PV recycling industry, so that a scenario with strong scaling effects is more likely to become reality.
- Fifth, potential firm specific 'internal' economies of scale were not taken into account in this study. Future research could investigate what the effects of internal economies of scale are on individual PV recycling firms. In the model a standard recycling facility size of 20 kt/y was assumed. However, it would be interesting to investigate the effects of an increase in size of a single PV plant on the average recycling process costs of this facility.

8 Conclusion

In this second-last chapter an answer is provided to the main research question. Based on a literature study and information obtained from field experts, a waste stream forecast model was built to find a meaningful answer to the following research question:

> *What is the economic potential of the PV recycling industry in Europe up until 2050, based on expected waste streams?*

Currently, as collected **waste volumes** are negligible, recycling is more expensive than the value of the potentially recovered material. In the first couple of years, waste volumes are predicted to stay relatively small, but, they are expected to increase significantly over the coming decades.

Waste volumes are rather unequally distributed among the European members states. As over 40 percent of total PV waste between 2021-2050 is expected to emerge in Germany, they will be Europe's PV waste hot spot for the years to come. Germany will face a real challenge to process the enormous amounts of PV waste expected in the country, while many other member states will struggle to collect large enough volumes to reach the capacities needed to effectively run their own PV recycling plant.

The value of the waste stream depends on the waste composition, recycling yields and the material prices of the scrap materials in the future. Based on current commodity prices and recycling yields of the FRELP process, the **cumulative value** of all PV waste in Europe, expected between 2021-2050, ranges from 8 G€ to 10.5 G€, depending on the amount of future installed PV capacity.

Although the cumulative material value over the coming decades is significant, to capitalize on the emerging waste streams, low **recycling costs** are essential. The three cost categories identified in this study were: disassembling, transportation and recycling process costs. As the annual waste volumes grow, the total costs are expected to decrease as a result of learning effects, a decrease in average transportation distance and external economies of scale in general. Even in a weak cost reduction scenario, the total costs are expected to decline significantly over the coming decades.

Comparing the recovered material value (€/t) with the estimated recycling costs (€/t), shows that there is definitely a possibility for **profitability** in the PV recycling industry. However, if and when a self-sustaining recycling industry becomes reality, depends on numerous variables. The most influential factors are *price fluctuations*, the amount of *cost reduction* due to the increasing waste volumes, *waste collection* and the chosen waste *transportation strategy*. All scenarios and the corresponding first year of expected profitability are shown in table 14.

Table 14: Expected first year of profitability for each scenario

Cost reduction scenario	**Transportation strategy**	**Expected first year of profitability**		
		Price +20 percent	*Current prices*	*Price -20 percent*
Weak (s1)	Without pre-treatment	2028	2031	N.A.
Weak (s1)	With pre-treatment	2023	2027	2041
Average (s2)	Without pre-treatment	2025	2028	2030
Average (s2)	With pre-treatment	2023	2024	2027
Strong (s3)	Without pre-treatment	2024	2026	2028
Strong (s3)	With pre-treatment	2023	2024	2026

As can be seen in table 14, in a favourable situation, profitability in the PV recycling market could be achieved as soon as 2023. However, in a more unfavourable situation, the market will potentially not break even in the coming decades.

The results show that the market is extremely vulnerable to price fluctuations. However, even in case of a 20 percent price reduction, if disassembling costs are covered by another party or subsidy and a pre-treatment strategy is utilized, PV recycling is expected to be profitable as soon as waste streams are large enough to run a FRELP facility at full capacity. This is expected to be in 2023.

Profitable PV recycling becomes more likely as the waste streams grow. To increase the probability of a profit in the PV recycling market, the following should be done:

- **Improve PV waste collection rates**. This increases the size of the recycling market and makes it more likely that the market benefits from economies of scale and learning effects.
- **Utilize a pre-treatment strategy**. This significantly reduces transportation costs and as long as it does not increase the process costs by a more significant amount, it could decrease overall costs. Therefore, it would be interesting to further explore the possibility of a pre-treatment strategy.
- **Start with a centralized recycling plant**. Waste streams are expected to be relatively small in first coming years. Therefore, to reach the capacity necessary to effectively run a recycling facility, it is essential for European member states to work together and cluster their PV waste.

Although some variables cannot be influenced, if the right strategies are deployed, there seems to be a good chance that the emerging PV waste streams in Europe could be transformed from trash to treasure over the coming decades.

9 Recommendations: future PV EoL management in Europe

The aim of this final chapter is to provide a number of specific recommendations for future PV EoL management strategies in Europe, to the members of the 'European Solar Initiative', the EU and the industry in general, based on the results of the waste stream and economic potential assessment. This chapter considers potential solutions for future reverse logistics, the second life of recovered materials, externalities in the PV EoL process and reduction and reuse of decommissioned panels.

9.1 Waste collection

As long as PV recycling is not profitable yet, when modules reach the end of their life, the costs and hurdle of managing dismantling, transportation and recycling of solar panels can dissuade PV producers from recycling PV waste (see chapter 3.2). In order to increase the waste collection rates throughout Europe, it seems best to oblige PV producers in every member state to pay a fee in advance that covers the transportation and recycling costs. Furthermore, it would be beneficial to clarify responsibility of dismantling in the WEEE directive and work with a similar payment system to cover dismantling costs.

The downside of such a payment system is that it might disincentivize producers and PV plant owners to invest in solar energy. An ideal financial scheme ensures circularity, while not hindering PV investment. The fees that are paid upfront by solar panel producers, are meant to cover the recycling costs incurred at the end of their lifetime, after approximately 25 years. However, as shown in the model, it is likely that in the coming 25 years PV recycling becomes profitable. Therefore, a strategy needs to be developed for how to transition from a situation where we pay for recycling, to one where the waste is valuable and PV recycling is a profitable business.

The EU might want to work with a financial scheme in which the party that pays for recycling today, can actually get a (partial) return on their prepaid fee, if the recycling process happens to be profitable in the future. This prospect might somewhat decrease the disincentive created by the prepaid recycling fee.

9.2 Decentralized pre-treatment

In order to utilize the pre-treatment strategy, decentralized collection points or nearby general purpose recycling facilities, could be equipped with the technology needed for the first material extraction step of the FRELP recycling process. Involving general purpose facilities that are connected to the WEEE recycling network can be especially beneficial, as it creates the opportunity to take advantage of the already existing WEEE recycling infrastructure.

9.3 Centralized recycling

Currently, the lack of homogeneity regarding PV recycling requirements among EU countries, make cooperation and centralized recycling more difficult (Franz & Piringer, 2020).

In order to enable EU member states to work together, cluster PV waste and recycle centrally, it would be useful to have an identical legislative framework regarding PV recycling in all EU member states. This should at least include clearly defined responsibilities for EoL management and a minimum requirement regarding the purities of the recovered materials, obliging high value recycling.

9.4 Future of the recovered materials

The results indicate that significant amounts of materials can potentially be recovered from the emerging waste streams. As Europe has only a few active mines (EC, 2017), producing raw materials (aluminium, copper, silver, glass and silicon) via PV recycling is a solid solution to increase economic security and level the playing field with other continents.

Most value driving materials in PV waste (aluminium, copper and silver) are non-ferrous metals and have an infinite recyclable life (TWI, 2021). If done correctly, also glass can be recycled endlessly without degradation of the material (Ardente et al., 2019). The recovered material can be used again in new solar modules or in various other (domestic) industries and applications.

Silicon is included in Europe's list of critical raw materials, due to its significant economic importance and relatively high supply risk (Ardente et al., 2019). The recovered silicon could be used for second-use solar panel applications or it could be applied in electric cars, as silicon is used in the anode of lithium-ion batteries (Kim, Chae, Ma, Ko, & Cho, 2017). The rapidly growing electric car industry presents a unique opportunity to the PV recycling industry, as more and more silicon is necessary for the production of car batteries.

9.5 Externalities

The externalities of the various steps in the PV recycling process have not been included in the recycling costs in the model. According to various studies, if done correctly, the environmental damage avoided by PV recycling clearly outweighs the environmental damage done throughout the recycling process (Latunussa et al., 2016; Markert et al., 2020; Smith & Bogust, 2018; Tao & Yu, 2015). However, as the PV recycling market is growing, it becomes more important to ensure that the EoL process is carried out in a sustainable way.

Currently, a significant share of carbon emissions in the PV EoL process come from transportation. It would be interesting to look into electrifying PV waste transportation by using electric trucks or trains, depending on the area.

The other main source of environmental impact is the plastic incineration process. Currently, incineration is carried out using an industrial furnace run on natural gas (Latunussa et al., 2016). In the future, hydrogen might provide a cleaner alternative. Furthermore, incineration of plastic, even in sophisticated incinerators, emit toxic pollutants (Council, 2013). For future research it might be interesting to investigate if there are other, more environmentally friendly, techniques available to replace the incineration process.

To incentivize sustainable recycling, governmental bodies might want to consider to give a subsidy to organizations that recycle in a more environmentally friendly way.

9.6 Reduce and reuse

Although recycling is essential for a circular solar panel industry, reducing waste or reusing old panels is considered preferable and both come before recycling in the waste management hierarchy.

9.6.1 Reducing waste

According to IRENA (2016), as a result of R&D, less raw materials will be necessary in solar panels produced in the future. The advantage of this development is that it will likely result in less toxic metals ingrained in the PV sandwich, which makes PV modules easier to recycle. The disadvantage for the PV recycling industry is that R&D will likely also result in a reduction of silver in PV modules. This will cause a decrease in overall value of the recovered material. However, as the recycling process would potentially become easier, also the recycling costs are expected to drop. For the PV recycling industry it is important to keep an eye on the developments in the PV production industry and its effects on the material composition of future waste streams, as it greatly affects potential profitability of the market.

Furthermore, to ensure PV modules can be recycled as efficiently as possible, design for disassembly should play a leading role in solar panel production. Further research is needed on how to design solar panels for maximum durability and at the same time for easy disassembly.

9.6.2 Reusing decommissioned panels

A certain percentage of the decommissioned panels present repair and second life opportunities. Even the regular-loss pattern, specifically used in the model to eliminate 'repairable modules' from the waste stream results, might include some panels that can potentially be sold on the secondary market.

In case of a possibility for a second life, it is often more economical to first sell the panels or components for a reduced price on the second-hand market and only recycle afterwards. These old repaired modules present an opportunity for developing countries with less financial resources, to generate relatively cheap renewable energy. However, there is a good chance that modules sold to developing countries eventually end up in a landfill, polluting the soil, as most developing countries do not have PV recycling legislation in place (Okoroigwe et al., 2020). Therefore, this is only a good strategy if recycling can still be guaranteed. This could be done by opening recycling facilities in these countries. However, the volumes will probably be too small to do this economical. Another option would be to pre-treat the panels in the respective country, decreasing the waste volume, before shipping the remaining waste back to Europe for the latter steps of the recycling process. Figuring out the best strategy to enable developing countries to engage in the PV industry, while still securing recycling of decommissioned panels, would be an interesting topic for future research.

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