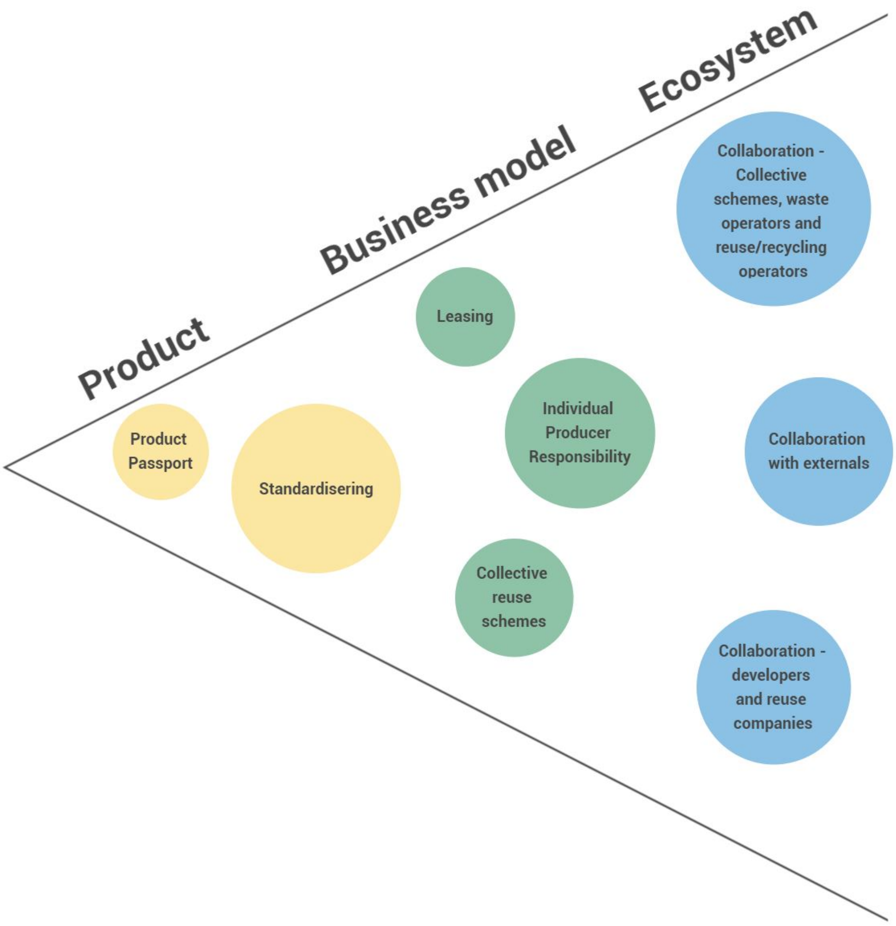
Aalborg University

Master's programme in Environmental Management and Sustainability Science

Master's Thesis

End-of-life management of photovoltaic panels



Furthering circular economy within the PV industry

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Abstract:

This study engages in recycling and reuse of photovoltaic (PV) panels. A literature review has been conducted to identify knowledge gaps within the topic. In order to examine this, the study answers the following research question:

What are the environmental impact of recycling and reuse of photovoltaic panels and how can further reuse be supported by actors involved in the end-of-life management from a Danish perspective?

To answer the research question, semi-structured interviews with actors related to the end-of-life (EoL) treatment of PV panels (developers, collective schemes, waste operators, and a trade association) have been included. The interviews are used to identify barriers that hamper the EoL management. The main barriers are associated with the low amounts of decommissioned PV panels. Additionally, life cycle assessment(LCA) is included to compare the environmental impacts of recycling and reusing 1m^2 of c-Si panels. The LCA shows that reusing PV panels causes the largest savings in terms of environmental impacts. Circular economy (CE) is included to suggest strategies that can further reuse. The strategies focus on reuse due to the results from the LCA. Furthermore, the strategies aim at decreasing the main barriers. Therefore, the recommendations engage in the *slow* circular strategy within the three innovation principles product, business model, and ecosystem. In terms of the product principle, it is recommended to include standardisation of the panels' size. Within the business model; leasing, individual producer responsibility, and collective reuse schemes are recommended. Finally, collaboration among the actors in the supply chain and collaboration with external actors are suggested as this can further the sharing of knowledge and experience across the industry. As these strategies aim at minimising the barriers and furthermore are within the slow strategy, it can be concluded that these can support actors to further reuse of PV panels.

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Preface

The master's thesis was completed between 01/02/2022 and 03/06/2022 during the fourth semester of Aalborg University's master's degree in Environmental Management and Sustainability Science. This rapport deals with the end-of-life of photovoltaic panels from a circular economy perspective. The results of this study can therefore be useful for actors within the end-of-life treatment of photovoltaic panels that have an interest in furthering circular economy through reuse of photovoltaic panels.

The thesis was carried out under the supervision of Anja Marie Bundgaard and Life Cycle Assessment consultant of Agneta Ghose. The project group wishes to express their gratitude to both for their guidance and support during the project.

Furthermore, the project group has benefited from the knowledge gained from various actors involved in the waste management of photovoltaic panels. Therefore, the project group would like to express its gratitude to the following respondents for taking the time to share their knowledge and perspectives on the study's research topic. Their participation has been essential to the project's success and analysis.

- Sustainable design engineer at Ennogie, Sebastian Hornbeak
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- Managing Director at Elretur, Morten Harboe-Jepsen
- Managing Director at Ragn-Sells, Massimo Forti
- Chairman of the Danish PV Association, Flemming Vejby Kristensen

Reading guideline:
The references in the thesis are formatted in the Harvard style, which means they begin with [Surname, year]. They are listed alphabetically in the bibliography at end of the thesis, with a letter distinguishing sources with the same author and year, such as [X, 2022a] and [X, 2022b].

Abbreviations:

B2B	Business-to-business
B2C	Business-to-consumer
CE	Circular economy
c-Si	Crystalline Silicon
DPA	Dansk producentansvar
EEE	Electrical and Electronic Equipment
EF	Envionmental footprint
EMF	Ellen MacArthur Foundation
EOL	End-of-life
EPA	Environmental Protection Act
EPR	Extended producer responsibility
EWO	The Electronic Waste Order
FU	Functional unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PV	Photovoltaic
RF	Reference flow
SOTA	State-of-the-art
WEEE	Waste from Electrical and Electronic Equipment

Summary

Udbygningen af solceller har de seneste 10 år gennemgået en markant stigning. Særligt markbaserede anlæg har oplevet et vækstboom. Dette afspejler sig også i Energistyrelsens fremskrivning for elektricitet produceret af solcelleanlæg. Heraf fremgår det, at elektricitet produceret af solceller vil overhale land- og havvindmøller. Dette indikerer, at udbygningen af solceller fortsat vil stige de kommende årtier, hvilket kan ses at være et resultat af de lavere omkostninger samt et øget fokus fra politisk side i at udbygge grøn energi. Solceller har gennemsnitligt en levetid på 25-30 år. På nuværende tidspunkt er den mest dominerende solcelletype Crystalline Silicon (c-Si) paneler grundet dens effektivitet samt lave produktionsomkostninger, hvilket forventes ligeledes at være gældende i de kommende år. På trods af den lange levetid, er et væsentligt aspekt, der skal tages i betragtning i takt med udbygningen, håndtering af udtjente panelerne. Dette ses i lyset af problematikken som opstod, da de første vindmøller skulle tages ned. Her var det vanskeligt og dyrt at genanvende vindmøllevingerne, hvorfor disse blev deponeret. Dette studier ønsker derfor at undersøge håndtering af solceller før de når endt levetid, for at imødekomme en lignende problematik. På det danske marked forventes der i 2050 at være 130.000 tons udtjente solcellepaneler. På nuværende tidspunkt reguleres affaldshåndtering af solceller igennem WEEE Direktivet på EU-plan, som overordnet implementeres i den dansk kontekst gennem Elektronikaffaldsbekendtgørelsen. Igennem et litteraturstudie er det identificeret, at fokusset hovedsageligt er på genanvendelse, hvilket kan ses som et resultat af WEEE-direktivet, som netop fastsætter, at 80% af produktet skal nyttiggøres og 85% skal forberedes med henblik på genbrug og genanvendes. Dette medfører dog, at solcellepanelerne på nuværende tidspunkt knuses, hvorefter materialerne udvindes. Dette studie undersøger, hvordan genbrug i højere grad kan blive implementeret i solcelleindustrien. Med afsæt i dette, besvarer studiet følgende problemformulering:

Hvad er den miljømæssige påvirkning af genanvendelse og genbrug af solcellepaneler, og hvordan kan yderligere genbrug understøttes af aktører involveret i håndteringen heraf fra et dansk perspektiv?

Til at besvare denne problemformulering, er der gjort brug af en mixed-method tilgang. Her er interviews med relevante aktører i branchen inkluderet, som en kvalitativ metode, samt en livscyklusanalyse af henholdsvis genanvendelse og genbrug er inkluderet, som en kvantitativ metode. Endvidere inddrages konceptet cirkulær økonomi, da dette centrerer omkring at undgå affald samt at levetidsforlænge produkter.

Interviews er anvendt til at kortlægge processen for håndtering af udtjente solcellepaneler, fra de tages ned til de sendes til genanvendelse eller genbrug. Ud fra denne kortlægning kan det konkluderes, at solcellepanelerne ikke bliver affaldsbehandlet i Danmark. Ved genanvendelse sendes panelerne til genanvendelsesoperatører i Tyskland eller Belgien. Dog

indebærer dette, at panelerne oplagres i Danmark indtil mængderne, er store nok til at kunne blive sendt videre. Derudover opbevares panelerne også i Danmark grundet manglende teknologi ift. affaldsbehandling. I forlængelse heraf anvendes interviews med aktørerne også til at udpege barrierer i forhold til genanvendelse og genbrug. Ud fra denne kortlægning kan det konkluderes, at den største udfordring på tværs af genanvendelse og genbrug er de små mængder af udtjente solcellepaneler, som skyldes den lange levetid. Endvidere kan det konkluderes, at WEEE-direktivet regulerer genanvendelse, hvorfor håndteringen heraf er etableret. I forlængelse heraf peges der endvidere på manglende fokus og viden vedrørende genbrug af solcellepaneler som en central barriere på tværs af aktørnetværket.

Gennem livscyklusvurdering af to scenarioer: genanvendelse og genbrug af 1 m^2 solcellepanel er det fundet, at genbrug medfører de største miljømæssige besparelser sammenlignet med genanvendelse. Endvidere er der foretaget sensitivitetsanalyse af resultaterne for at teste, hvordan ændret data input samt effektiviteten og dertilhørende levetid spiller ind på resultaterne. Herfra kan det konkluderes, at aluminium og silicium har den største påvirkning på genanvendelse scenariet. Ydermere kan det konkluderes, at energi påvirker genbrugsscenariet mest. Afsluttende er det undersøgt, hvordan degrationsraten påvirker levetiden. Herfra kan det konkluderes, at solceller potentielt har en længere levetid end de 30 år. Dette afhænger af deres degrationsrate samt hvilket klima de befinder sig i. Livscyklusanalyserne understreger således, at genbrug bør prioriteres for at mindske den miljømæssige påvirkning sammenlignet med genanvendelse.

Cirkulære strategier er blevet udarbejdet som initiativer til at fremme genbrug af solcellepaneler. Herunder er strategier inden for *"slow"*, præsenteret af Konietzko et al. [2020b], blevet valgt, da dette princip hviler på levetidsforlængelse. Dette valg er truffet på baggrund af livscyklusanalyserne, som har påvist at genbrug er mest fordelagtigt miljømæssigt. Inden for dette princip er det vurderet relevant at udarbejde strategier, som tager afsæt i innovations principperne produkt, forretningsmodel og økosystem. Det er centralt at inkludere de tre perspektiver for at den cirkulære omstilling kan finde sted. Til udarbejdelsen af disse tages der udgangspunkt i de barrierer, som aktørerne har peget på. Dette er med antagelsen om, at ved at mindske de barrierer, der peges på i branchen, er det muligt at fremme genbrug af solcellepaneler. Indenfor produkt foreslås det, at der indføres standardisering af størrelsen af solcellepanelerne, da dette gør dem mere kompatible. Indenfor forretningsmodellen er der foreslået tre strategier; leasing, take-back systemer samt kollektive ordninger, som varetager genbrug. Disse forretningsmodeller skal bidrage til, at der skabes et incitament for udviklere, importører og de kollektive ordninger til at prioritere genbrug. Afslutningsvis anbefales det, at der etableres partnerskaber på tværs af aktørkæden, som udspringer af økosystemsperspektivet. Dette muliggør, at erfaringer og viden kan deles blandt aktører, hvormed denne barriere mindskes. Her er der særligt fokus på partnerskab og samarbejde mellem de kollektive ordninger, affaldsoperatører og genanvendelses-/genbrugs operatører. Denne anbefaling skal fremme, at aktører på tværs af aktørnetværket prioriterer genbrug. Derudover anbefales det også, at udviklere og genbrugsoperatører skaber et samarbejde. Derved kan der udveksles erfaring med, hvordan panelerne skal tages ned, således genbrug i højere grad kan finde sted. Med afsæt i disse anbefalinger kan det konkluderes, at disse vil støtte aktørerne i at prioritere og derved fremme genbrugen af solcellepaneler.

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1 Development of photovoltaic panels

The use of fossil fuels is the largest contributor to global warming which entails climate changes [Letcher and Fthenakis, 2018] and today's electricity is heavily dependent on fossil fuels. However, this source is estimated to diminish in approximately 50 years [Yudha et al., 2018]. The influence on climate change and fossil fuels as exhaustible resources combined with humans' dependency of electricity are some of the important reasons for increasing the share of renewable energy. The implementation of renewable energy will contribute to a reduction in global warming and the problems related to air pollution. Additionally, the use of renewable energy will help overcome the dependence on the limited fossil fuels and thereby increase the energy security [Seo et al., 2021].

According to IEA [2021a], the use of renewable sources remained successful during COVID-19 with a growth of 3% in 2020 and an increase in the key sectors – power, heating, industry, and transportation. The share of renewable sources in the global electricity generation was in 2020 29% and was set to expand by more than 8% in 2021 with photovoltaic (PV) and wind expected to contribute with 2/3 of the growth [IEA, 2021a]. PV accounted for 3,1% of the global electricity generation in 2019 and is the third-largest next to hydropower and onshore wind [IEA, 2021b]. In addition, PV is one of the industries with the fastest growing with a growth rate of 35-40% per year [Seo et al., 2021]. Figure 1.1 illustrates that the PV industry is relatively new as the development has started to rise more rapidly since 2015. Additionally, the projection of capacity emphasises that the industry is fast growing.

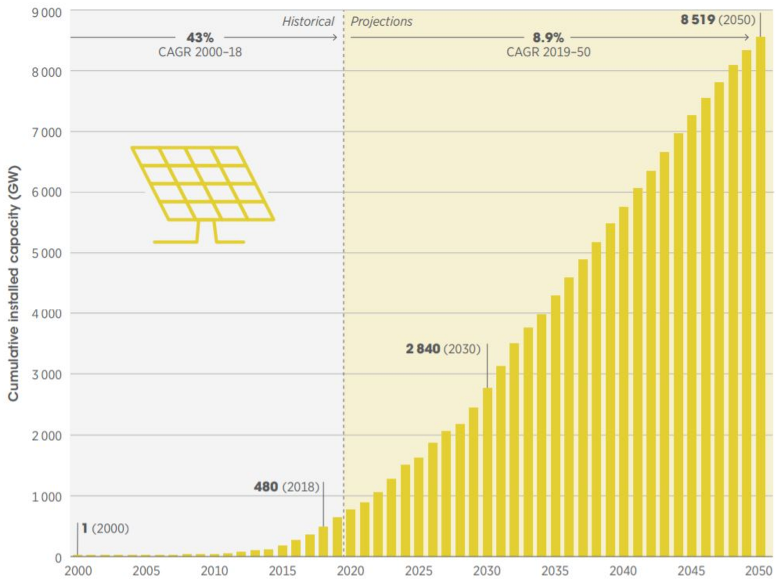


Figure 1.1. Global installed PV capacity from 2000-2019 and projection of the growth in the PV capacity from 2020-2050 (GW) by IRENA [2019]

Further, PV is an attractive alternative to the substitution of fossil fuels as it is considered safer, no-pollution reliable, maintenance-free, and has a long lifetime of around 20-30 years. Additionally, it allows being installed anywhere, if sunlight is present and the scale is depending on the energy requirements [Yudha et al., 2018]. Finally, PV is also beginning to have prices that can compete with energy from coal, gas, and oil [Letcher and Fthenakis, 2018]. In the EU, the *Renewable Energy Directive* [1], is the overall directive that affects the implementation of solar energy. This directive establishes common principles and rules to guide the development of renewable energy in all sectors of the EU economy. The aim is to remove barriers, stimulate investments, drive cost reduction, and empower citizens, consumers, and businesses to participate in the transition to renewable energy [European Commission, 2022c]. The directive is currently under revision since the targets need to be aligned with the European Green Deal in order to deliver on the increased climate ambitions, which is set in this deal. One of the elements that need revision is the current target of 32% renewable energy by 2030, as it is not sufficient. Therefore, the target needs to be increased to 38-40% [European Commission, 2022c]. However, on the 18th of May 2022, the European Commission presented the RePowerEU plan as a response to Russia's invasion of Ukraine, which has disrupted the global energy market. The plan has the aim of ensuring "energy savings, diversification of energy supplies, and accelerated roll-out of renewable energy" [European Commission, 2022d]. This plan entails a further increase of the renewable energy target to 45%. Additionally, the plan has concrete targets regarding solar energy. The reason for the increased focus on solar energy is because it is one of the fastest technologies to roll out. One of the targets is to install 320 GW by 2025, which exceeds over twice the amount of today's amounts. Furthermore, the plan introduces a legally binding obligation for installing PV panels on rooftops for selected building types [European Commission, 2022d].

In Denmark, the use of solar energy will increase like the general development. In 2030 the danish electricity production will primarily consist of solar and wind energy, which is expected to reduce the emissions by 95% as a result of i.a. phasing out coal in the electricity and district heating sector. Figure 1.2 illustrates the development of the total capacity from solar compared with wind on-shore and off-shore.

[1] Directive 2018/2001/EU of the European Parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources

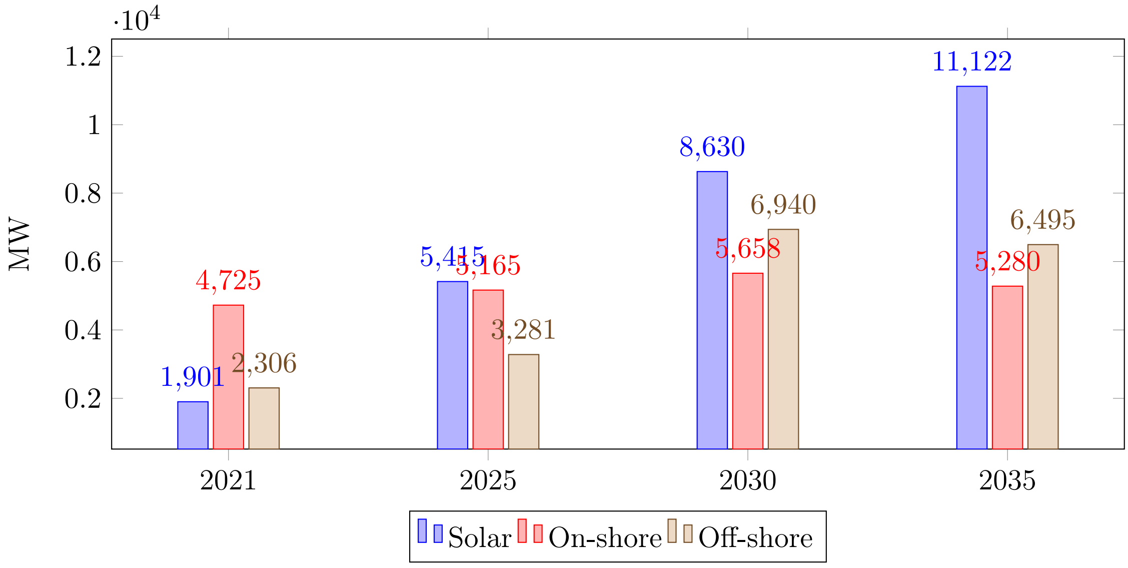


Figure 1.2. Danish development of the total capacity from solar, wind on-shore, and off-shore [Energistyrelsen, 2022]

As figure 1.2 shows the total capacity of solar will increase significantly in the coming year and will exceed wind in 2025. This means that more PV panels will need to be waste treated in the future.

1.1 Types of PV panels

There exist roof-mounted and ground-mounted PV panels. Therefore, the panels can either be used as single modules or as multiple modules that represent an array [Letcher and Fthenakis, 2018]. The construction of the panels themselves is the same regardless of the type of installation. However, the sizing varies according to the type of installation. The roof-mounted panels are placed on top of the roof of buildings, see figure 1.3, and does ideally face the south for optimal utility. Alternatively, the panels are integrated into the roof, see figure 1.4. Here, the solar cells are integrated into the materials used in the roof [Letcher and Fthenakis, 2018]. The roof-mounted and integrated PV panels are mainly integrated by private households, private companies, local authority-owned buildings, or public buildings [Letcher and Fthenakis, 2018; Kristensen, 2022]. The ground-mounted PV panels are free-standing and are used in solar farms. Here, the PV panels are arranged in arrays and obtain a larger amount of land. The panels are mounted on frames and elevated from the ground. As for the roof-mounted panels, the ground-mounted panels should also face the south [Letcher and Fthenakis, 2018]. The ground-mounted panels can either be fixed-tilt with the same position, see figure 1.5, or use the tracker technology, see figure 1.6. The tracker technology allows the panels to adjust according to the course of the sun. However, the tracker technology entails greater maintenance [Letcher and Fthenakis, 2018].

Figure 1.3. Illustration of roof mounted panels by Kiis [2021]

Figure 1.4. Illustration of integrated roof panels by Ennogie [2018]

Figure 1.5. Illustration of fixed tilt panels by Letcher and Fthenakis [2018]

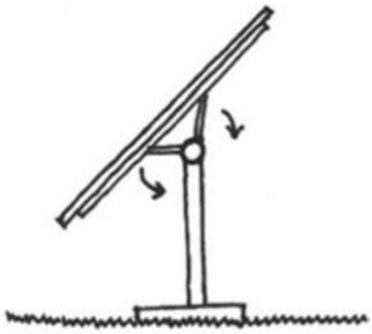


Figure 1.6. Illustration of tracker technology panels by Letcher and Fthenakis [2018]

Figure 1.7 illustrates the development of the total capacity from solar energy distributed on roof and ground panels.

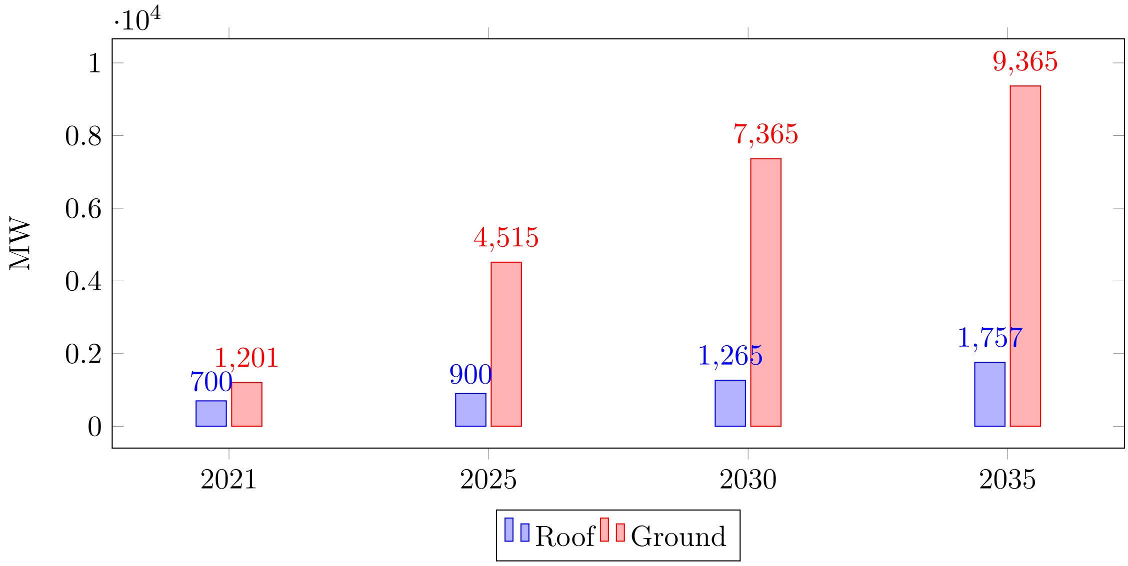


Figure 1.7. Development of roof- and ground-mounted PV panels in Denmark 2021-2035 [Energistyrelsen, 2022]

Figure 1.7 shows that the ground-mounted panels will be the dominating panel type used in the Danish context. Frahm [2022] states that one reason for the lack of increase in the roof-mounted PV panels compared with the ground-mounted is caused by the lack of subsidies, which have been removed for a while. In continuation of this Kristensen [2022] stresses that the current increase in roof-mounted PV panels is mainly due to companies installing PV panels in their building. Nevertheless, the subsidies are starting to be implemented again, which according to Frahm [2022] will entail an increase in the amount of roof-mounted PV panels. Furthermore, the increase in the roof-mounted panels can also be caused by the increased use of building certifications such as DGNB, which is the most used building certification scheme in Denmark [Miljøministeriet, 2021]. This is because PV panels can be used to achieve points in different criteria in the DGNB certification. Additionally, as previously mentioned, the new RePowerEU plan has made obligations regarding the installation of roof-mounted PV panels. The concrete obligation state that all new construction of major commercial and public buildings from 2025 and all new building from 2029 must install PV panel on rooftops. This will affect the development of roof-mounted PV panels in the coming years [DR, 2022].

The PV panels used in the market can be grouped into three different PV technologies. These technologies are further divided into three generations:

- First generation (c-Si)
- Second generation (thin-film)
- Third generation: Concentrative Photovoltaics CPV and emerging technologies

The most used PV technology is the first-generation silicon-based panels which comprise the majority of the installations worldwide with approximately 85-90% [Daljit Singh et al., 2021; Mahmoudi et al., 2019]. The second-generation (thin-film) based panels account for approximately 9% whereas the third generation panels are still under development and only in the pre-industrial stage. The c-Si panels are extrapolated to remain the most dominant technology in the coming decade. However, the current c-Si technology will decrease to account for 44,8% of the PV market in 2030. Instead, advanced crystalline silicon (advanced c-Si) panels will increase and become the second most dominant by representing 25,6% of the market share in 2030 and thereby exceeding the share of thin-film based panels [Sica et al., 2018]. Some of the reasons why silicon-based panels are widely used are because they can be produced easily, cheap, and are efficient. Further, their material composition makes the panels highly recyclable as they mainly consist of glass, aluminium, silicon, and plastic and only a small amount of other materials like silver, tin, and lead [Daljit Singh et al., 2021].

1.2 PV waste management

Despite the growth and the benefits of using PV panels, it also entails a new challenge in the end-of-life (EoL) management of the PV panels [Daljit Singh et al., 2021]. When comparing the PV industry to the wind industry, the need for proper EoL treatment is further emphasised. The wind industry did also experience rapid growth in the development of wind turbines. However, when wind turbines reach their EoL, the problem occurs as the blades are difficult and expensive to recycle. Therefore, the EoL treatment of the blades has been through landfilling where these are piling up in "blade mass graves" [McFadden, 2021]. In order to avoid a similar scenario for the PV industry, it is deemed relevant to investigate the waste management hereof prior to the increased amounts of PV waste will occur on the market. Figure 1.8 illustrate the estimation of the global EoL PV waste generation based on two scenarios; a regular loss based on the lifetime of the PV panels and an early loss which can be caused by several different factors such as damage caused by e.g. extreme weather, technical failures, repairable modules that are replaced with new ones, or repowering [Mahmoudi et al., 2021; ISES, 2020; Daljit Singh et al., 2021].

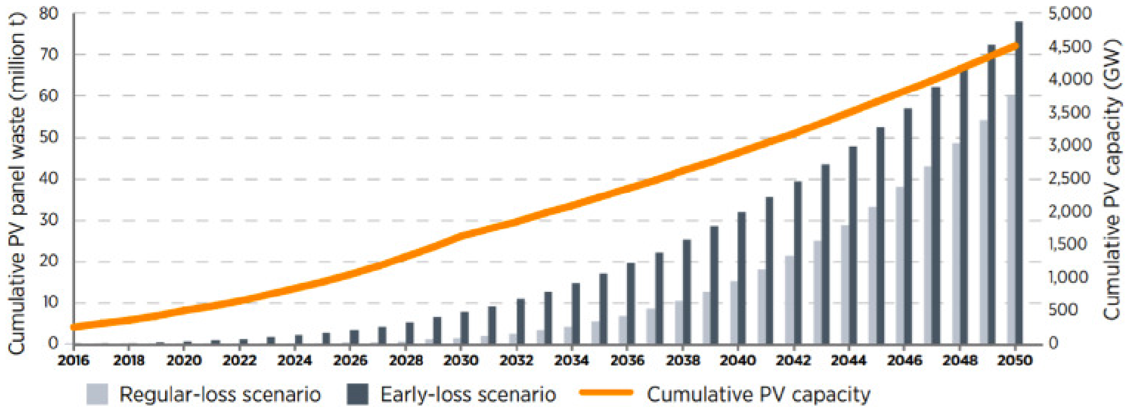


Figure 1.8. Estimation of Global EoL PV waste generation by Mahmoudi et al. [2021]

Further, the figure 1.8 illustrates that the waste generation has started and will only increase in the coming years which indicates the need for action on the waste management now although the quantities remain relatively small. Currently, the waste management of PV panels is still under development since it is not economically viable yet [Franz and Piringer, 2020]. However, markets for recycled parts of the panel such as the aluminium frame exist [Kristensen, 2022]. In the preparatory study of *PV modules, inverters, and systems* by Dodd et al. [2019] it is presented that the current waste management of PV panels in the EU is dominated by dismantling, recycling, and disposal. Further, the amount of PV waste in Denmark will likewise increase in the coming decades. GreenMatch [2021] has estimated the specific amount of PV waste that will be generated in Denmark, which is listed below and has its starting point in 2016.

- 2016: 80 tons
- 2020: 100 tons
- 2030: 4,000 tons
- 2040: 40,000 tons
- 2050: 130,000 tons

However, these waste estimations do not completely correspond to the collected quantities. In 2021 only around 30 tons of PV panels waste was generated and collected [Frahm, 2022; Harboe-Jepsen, 2022]. Nevertheless, the amount of generated waste could result in critical environmental effects if it is not managed properly [Daljit Singh et al., 2021]. Here, the waste hierarchy is a framework that prioritises the treatment of waste according to what is more beneficial environmentally. The waste hierarchy is part of the Waste Framework Directive [2] which is the overall framework for waste management. The waste hierarchy, as

[2] Directive 2008/98/EC

seen in figure 1.9, illustrates a prioritised way to manage and treat waste to achieve results that benefit the environment.

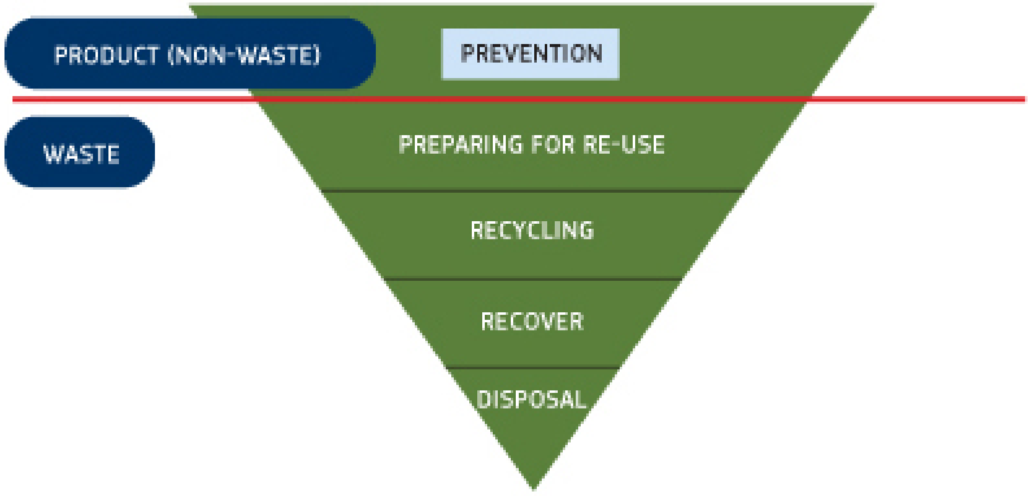


Figure 1.9. European Union's Waste Hierarchy [European Commission, 2022h]

As figure 1.9 illustrates, the level "prevention" is the preferred option but it is not a part of the waste management as it is related to products before they are categorised as waste. The least preferred option is disposal where the waste is sent to landfilling and should be the last resort. PV panels are currently waste treated at the three lowest levels of the hierarchy; recycling, recovery, and disposal.

There are numerous recycling technologies and some of them are reaching a recycling efficiency of 96% [GreenMatch, 2021]. The recycling technologies that exists can be classified into two overall categories: bulk recycling and high-value recycling. Bulk recycling focuses on recovery of high mass fraction materials which are materials such as glass, aluminium, and copper while high-value recycling also has a focus on semi-conductor and trace metals [Dodd et al., 2019]. The most common approach in the PV industry is bulk recycling which is using a process of crushing and grinding. There are different treatment methods for the waste PV panels and these can be categorised into mechanical, thermal, and chemical treatment. These methods can also be used in a combination to treat the waste. The thermal and chemical treatment provides the highest-value recycling [Dodd et al., 2019]. However, despite the high recycling efficiency, the resources have different criticality. Therefore, it is necessary to consider the criticality of the raw materials when recycling which can be assessed based on economic importance and supply risk [Dodd et al., 2019]. PV panels have received specific attention regarding the criticality of the raw materials since materials such as indium, gallium, and silicon metal are identified as being of particular relevance to circulate. Further, these also have a potential for economically feasible recycling [Dodd et al., 2019]

Dodd et al. [2019] estimates that in the next 10-15 years approximately 80% of the PV waste will consist of panels with premature failures rather than panels that have reached EoL. Based on this, it has been estimated that 2/3 of these panels may be possible to repair or refurbish which enables 50% of the waste could avoid the waste stream and the recycling path [Dodd et al., 2019]. Another reason why the lifespan of the panels varies is due to the context of the use. Households tend to keep the panels longer since optimising the financial return is not their primary interest. The owner in the context of utility-scale solar farms, on the other hand, tries to optimise their returns since it is an investment. Therefore, replacing the PV panels before they reach EoL is more likely due to the economic perspective [WEEE Forum, 2021].

Today reuse, repair, and refurbishment are rather informal in the PV industry. These are currently performed by private companies without interaction or support from the original manufacturers. Further, the current PV panels are not designed to facilitate an effective separation of the used materials at EoL which entails low-value recycling and landfilling [Franco and Groesser, 2021]. Reuse of PV panels is a nascent industry where the actors are operating in an unexplored and unregulated area with little or no knowledge of its operations [PV Cycle, 2022]. Additionally, there are limited standards for testing, certification, and labeling of refurbished PV panels. The market for repair or refurbished PV panels is primarily based on rebranding and further sold to less-developed electrified markets. Only a limited amount of these panels are sold on the European markets. Since the industry is informal and rather young, no data is available on the reuse, repair, and refurbishment of PV panels [Dodd et al., 2019]. Reuse, repair, and refurbishment have an essential role in the circular economy (CE) since these processes aim for extending the lifespan of the PV panels and thereby preventing an early entry into the waste stream [PV Cycle, 2022].

1.2.1 Waste management legislation

The legal framework for waste management of PV panels is presented in the following sections. The legislation is an instrument to accommodate and handle the increasing amounts of PV waste and furthermore to ensure that these are handled in a more environmental-friendly way.

WEEE Directive

Most countries globally consider the waste generated by PV panels as "general waste" which entails that the panels cannot be recycled [Dodd et al., 2019; Ndzibah et al., 2021]. However, the PV panels are recyclable, but it is comprehensive to get it widely implemented since it also needs further research on the recycling methods to reach the full potential of all the components [GreenMatch, 2021; Dodd et al., 2019]. A way of accommodating the increased amounts of PV waste and the treatment hereof is through legislation. The European Union (EU) was the first to develop specific waste regulations concerning PV panels which were adopted in the Waste Electrical and Electronics Equipment (WEEE) Directive [3] in 2002 and was lastly amended in 2012. The directive further includes PV-specific collection, recovery, and recycling targets [Ndzibah et al., 2021]. Since 2014, PV panels and inverters have been included in the scope of the WEEE Directive. PV panels are categorised as “large equipment” and thereby regulated by annex III category 4 [Dodd et al., 2019]. The aim of the directive is:

[3] Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE)

"to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste from electrical and electronic equipment (WEEE) and by reducing overall impacts of resource use" cf. WEEE Directive.

Furthermore, the directive extends the view on EoL by focusing on the product's whole lifespan through general objectives cf. WEEE Directive;

- *"preventing the creation of WEEE as a first priority"*
- *"contributing to the efficient use of resources and the retrieval of secondary raw materials through re-use, recycling and other forms of recovery"*
- *"improving the environmental performance of everyone involved in the life cycle of EEE"*

Based on the overall objectives, the directive sets up common rules and environmental targets regarding the waste management of EEE. For products listed in annex III category 4, the recovery should be 85% and 80% should be prepared for reuse or recycling [European Commission, 2022f]. It is expected that the global PV waste will account for approximately 10% of all WEEE generation in 2050 [Daljit Singh et al., 2021]. In a Danish context, the recovery and recycling rates for PV waste have not yet been calculated and compared with the specific recovery and recycling targets from the WEEE Directive. This is due to the relatively limited amount of waste which entails limited corresponding amounts going to the waste management [Miljøministeriet, 2021].

Extended Producer Responsibility

An essential aspect of the WEEE Directive is that it includes an extended producer responsibility. This means that the developers and importers of PV panels are responsible for the product throughout the whole lifetime. In this regard, they are responsible for financing and organising take-back schemes and waste treatment of the product. In addition, the developers or importers of a product covered by the WEEE Directive are obliged to register in the national producer register, assign the products with a pictograph, register the quantities of the marketed and taken-back products, and the composition hereof cf. the WEEE Directive. In the EU, the collection of the PV waste is coordinated by Producer Responsibility Organisations. The small quantities, such as household PV waste, are collected based on take-back infrastructures like certified collection points or municipal collection sites. For the larger quantities such as professional sites or solar farms, the waste management is done through tailored on-site pick-ups [Dodd et al., 2019].

As Denmark is part of EU [European Union, 2022], they are obliged to implement the regulation regarding collecting and waste treatment of EEE in a matter that benefits the environment. This further entails that Denmark should reach the same percentage for recovery and preparation for reuse or recycling of EEE products. However, reuse of EEE products is still a limited market, and the percentage of reuse of EEE products in Denmark in 2020 was limited to approximately 2% compared to 82,5% of the EEE waste that were recycled [DPA, 2022a]. The WEEE Directive is implemented in the danish legislation through the *Environmental Protection Act* (EPA) [4] and *The Electronic Waste Order*

[4] Consolidated Act no 100 of 19/01/2022, Declaration of the Law on environmental protection

(EWO) [5]. The aim of EPA is to protect and preserve the environment and nature in the development of society and ensure that this is done sustainably. The waste hierarchy is implemented through the EPA. The specific regulation on waste management of EEE is specified in the EWO which emanates from the EPA. Therefore, the extended producer responsibility is regulated in a danish context through EWO. According to EWO, Dansk Producentansvarssystem (DPA) is responsible for the danish digital register of producers. DPA is a danish organisation that was originally established in connection with the establishment of EPA. The purpose of the organisation is to manage the rules regarding the extended producer responsibility. In addition, DPA operates the producer responsibility register where cf. EWO the producers are obliged to register.

According to DPA, the following groups are covered by the extended producer responsibility: a danish-located company that produces a product covered by the WEEE Directive, an importer that is located in Denmark which resells a product in Denmark that is covered by the WEEE Directive, or a foreign company where the end-consumer of the product is located in Denmark [DPA, 2022c]. An importer or producer can either choose to handle the tasks associated with the extended producer responsibility themselves or they can enter into a collective scheme. The WEEE fractions are sorted into six categories which are:
1. Big equipment over 50 cm such as Appliances
2. Equipment for temperature exchange such as refrigerators and freezers
3. Small equipment and small IT under 50 cm
4. Screens and monitors such as tablets and laptops, but not mobiles
5. Light sources
6. Photovoltaic panels

These fractions are managed by the following five collective schemes, which are managing different fractions [DPA, 2021]:

- Elretur: fraction 1, 2, 3, 4 and 6
- European Recycling Platform (ERP): fraction 1, 2, 3, 4 and 6
- Recipo: Fraction 1, 4 and 6
- RENE AG: fraction 1, 2, 3 and 4
- Lyskildebranchens WEEE Forening (LWF): fraction 5

The collective schemes are services where the importers or producers pay a fee to become part of the collective scheme. Different tasks and responsibilities associated with the extended producer responsibility are thereby handed over and managed by the collective scheme [DPA, 2022b]. However, cf. EWO there is a differentiation between household waste and business-generated waste. The household-generated waste will be managed through established collective schemes. These collective schemes shall establish collection points in each region. As opposed, the waste generated by a business must at its own expense take back waste and secure proper waste treatment.

[5] Consolidated Act no 1276 of 06/06/2021, Executive Order on placing electrical and electronic equipment on the market and handling of waste electrical and electronic equipment

RoHS Directive

Another aspect that needs to be considered in terms of waste treatment of PV panels is hazardous substances. The WEEE Directive is supported by the Restriction of the Use of Certain Hazardous Substances Directive (RoHS) which regulates and restricts the use of hazardous materials in EEE. The main objective of this directive is to protect the environment and human health from certain hazardous substances (i.g. heavy metals, flame retardants, and plasticizers) in EEE by putting restrictions on the use of these substances and suggesting substitution with safer alternatives [European Commission, 2022e]. It is relatively small amounts of the PV panels (i.g. 2% of the thin-film panels) that are considered hazardous waste [Ndzibah et al., 2021]. However, the hazardous substances in the panels make the EoL handling more costly and complex [Fthenakis, 2000]. Therefore, avoiding these substances further the recyclability of EEE [European Commission, 2022e]. The RoHS Directive is implemented in the danish context through the *RoHS act* [6] where PV panels are regulated by §1, pcs. 8.

Ecodesign Directive

Ecodesign Directive features regulation on the design of products and aims to reduce the environmental impacts of EEE products. Thereby, the Ecodesign Directive sets requirements for the design of a product which can contribute to furthering the EoL treatment [Zacho et al., 2018]. The Ecodesign Directive [7] is one of the most effective policy instruments at the EU level to promote energy efficiency [European Commission, 2016]. It is a framework where manufacturers of energy-related products are obligated to reduce the energy and other negative environmental impacts from a life cycle perspective. The manufacturers must meet the performance criteria in the framework to legally bring the products to the market. Ecodesign Directive is complemented by the Energy Labelling Directive where the requirements aim at providing information about the performance of the products to the customers. It is estimated that these two directives contribute with approximately half of the energy-saving targets for 2020 [European Commission, 2016]. However, PV panels are currently not a part of the Ecodesign or the Energy Labelling Directives. The Ecodesign Directive has a working plan with a list of prioritised product groups that could be included in the framework. In the period June 2020 - to January 2021 a joint mission group with representatives of the PV value chain has reviewed the results of the preparatory study of *PV modules, inverters, and systems* and provided recommendations. The development of the potential requirements in the Ecodesign has started and will further take place during 2021 and 2022 [ETIP PV et al., 2021]. Additionally, the newest Ecodesign Working Plan 2022 - 2024, which was published on the 30th of March 2022, has a strengthened focus on the circularity aspects of ecodesign and labeling [European Commission, 2022g]. Further, the working plan highlights, regarding PV panels, that the work is well advanced and it is time to access the feasibility of ecodesign requirements and energy labeling for PV panels [European Commission, 2022b].

In order to achieve waste treatment on the higher levels of the waste hierarchy, it is relevant

[6] Consolidated Act no 1943 of 13/10/2021, Order restricting the use of certain hazardous substances in electrical and electronic equipment in the EU

[7] Directive 2009/125/EC of the European Parliament and of the council of 21 October 2009 - establishing a framework for the setting of ecodesign requirements for energy-related products

to include the concept of CE. The legislation does to some extent support the transition towards CE [Zacho et al., 2018]. However, the current waste legislation focuses on materials when it is characterised as waste. Proper waste management is important; however, it is just as important to move away from the concept of waste in order to transition into a CE. The concept of CE will therefore be elaborated upon in the following section.

1.3 Circular economy

Circular economy is a young field with various possibilities for defining the concept [Kirchherr et al., 2017]. However, there is no commonly accepted definition of CE, but the most prominent CE definition is provided by Ellen MacArthur Foundation (EMF), which is:

> *"an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."* [Kirchherr et al., 2017].

The CE model is a counterpart to the dominant linear economic model. The linear take-make-dispose culture is dependent on easily accessible resources and energy, making it unfit for the reality in which it operates. The CE model aims to keep products, components, and materials at their highest utility and value [EMF, 2015]. EMF distinguishes between two cycles a technical and biological cycle. In the technical cycle, the aim is to maximise the value of technical assets and materials which entails that the structural waste will be addressed in industrial sectors. Further, in the biological cycle, the aim is to create flows that do not exceed the carrying capacity of natural systems [EMF, 2015]. This study has its focus on the technical cycle due to the focal point on PV panels.

As an extension of EMF's description of the concept of CE, some of the latest research is about how CE can be operationalized. Among others, Konietzko et al. [2020b] describe five interconnected circular strategies; narrow, slow, close, regenerate and inform, which can be used to prioritise CE. The strategies will be further elaborated in chapter 4.2 and are supporting the description of CE by EMF. However, the focus on information as an important instrument in the transition to CE differs. The use of renewable energy is an important aspect in both frameworks for CE. Therefore, the use of solar energy will be an important element in the transition to CE. However, it is essential that the EoL of the PV panels is managed in a circular perspective to support the transition and keep the PV panels, components, and materials in circulation.

The following section will include a literature review of the existing knowledge and literature on the topic of this study. This is performed to investigate the current knowledge and possible knowledge gaps in which this study seeks to contribute with new aspects.

1.4 State-of-the-art analysis

A literature review of the relevant literature in terms of PV waste management has been included to investigate the waste management of PV panels and how this affects the environmental impacts hereof. Here, life cycle assessment (LCA) is a useful tool to quantitatively investigate the environmental impacts of a certain product or service throughout its lifetime [Matthews et al., 2015]. However, the focus in LCA studies on PV panels has primarily been on the cradle-to-grave perspective. Thereby, research in this field has generally neglected to focus on the cradle-to-cradle perspective [Contreras Lisperguer et al., 2020]. Therefore, a state-of-the-art (SOTA) analysis has been conducted in order to identify and examine the current literature in the field. This is done to obtain knowledge on the field and furthermore to explore possible knowledge gaps where this study can contribute with knowledge and build upon the existing research.

During the initial search, a couple of systematic literature reviews on the EoL of PV were identified. One of these is conducted by Mahmoudi et al. [2019] which summaries 70 articles regarding EoL of PV panels. In the review, it is identified that only a limited number of the articles include LCA with the EoL phase.

Based on this, the literature review seeks to identify literature where the EoL phase is included in the LCA of the PV panels. Furthermore, the literature review seeks to investigate the current focus on the EoL treatment of PV panels. A more thorough description of the systematic approach to the literature review is presented in section 3.1. In the following sections, the key findings of the literature review will be summarised and potential knowledge gaps will be highlighted.

The distribution of the articles in the past five years is shown in figure 1.10.

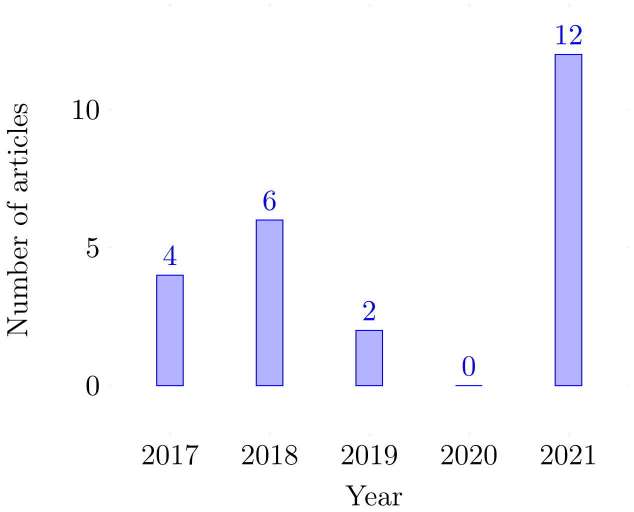


Figure 1.10. The distribution of the articles during the last five years

The increase in the published articles in the last five years indicates the rising interest in the research field of EoL and LCA in terms of PV panels which is why it is deemed relevant to examine this field further. In addition, most of the studies are focusing on developed countries and there are only five articles that focus on developing countries. Furthermore, none of the identified articles are focusing on the topic in a danish context. This leaves a gap in terms of investigating the field from a Danish perspective.

Type of PV technology

The circle chart in figure 1.11 shows the distribution of the different types of PV technology.

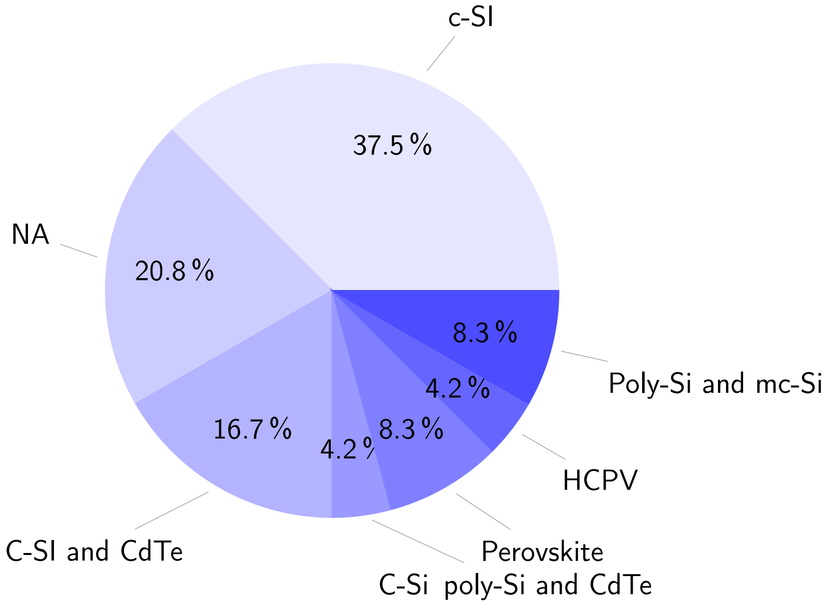


Figure 1.11. Percentage distribution of PV technology types found in the articles

Five of the articles did not specify the PV type included in the study. Most of the articles (9) focus on crystalline silicon (c-Si) PV. In addition, five articles also include c-Si PV among other PV types such as Cadmium telluride (CdTe) and Poly-crystalline silicon (poly-Si). This can be explained by c-Si PV being the first PV generation and the most dominant globally [Sica et al., 2018; Daljit Singh et al., 2021]. However, from the literature review, it can be deduced that there is an increasing focus on perovskite PVs which are the third generation.

Waste management

The waste management of PV panels in the articles is dominated by recycling, as figure 1.12 illustrates. Only seven articles consider waste management at the higher levels of the waste hierarchy which shows that limited focus has been given to these levels. Based on the waste hierarchy, the higher levels decrease the processing of the waste. However, due to the limited literature on this field, investigation regarding waste management of PV panels on the higher levels in the waste hierarchy is therefore needed.

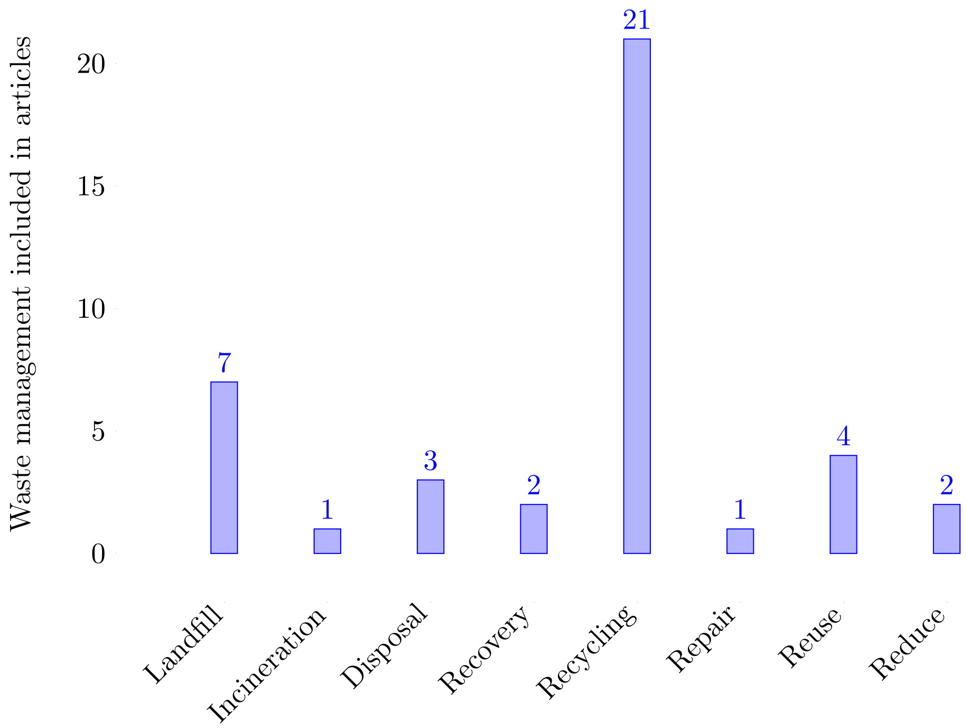


Figure 1.12. The distribution of the waste management of PV waste.

Some of these categories are covered by the same process but use different terms. Landfilling and disposal are used interchangeably. When disposal is used the assumptions are made that this is done through landfilling. Recycling is used to describe when the materials of the products are recovered and used again. Repair is when there are failures that counteract direct reuse which is why repair is necessary. Reuse covers when the modules can be reused through maintenance and repair are not needed. However, in some of the articles reuse does also cover repair. Reduce is when recycled materials are used which reduces the use of new materials and thereby the environmental impacts of the PV panels. Additionally, based on the categorisation of the waste management in the articles, it can be deduced that waste management terms are used interchangeably as some articles use different terms for an identical process which indicates uncertainty regarding what the respective waste management terms cover.

Circular economy

As mentioned in section 1.3, CE is a newer concept. In the field of EoL of PV panels, it is therefore deemed relevant to deduce if and how the identified literature introduces the concept. Out of the 24 articles, eight articles mention CE in relation to the waste management of PV panels. However, the majority of these studies briefly mention the concept in relation to how the waste management of PV panels contributes to circularity. The concept is therefore not elaborated upon and neither used actively in the transition of the waste management of PV panels. This is also emphasised in the study by Santoyo-Castelazo et al. [2021] in which it is stated that there is a lack of CE actions in the PV industry. Additionally, a literature review conducted by Franco and Groesser [2021] concludes that research on circular strategies and design in terms of PV panels is limited.

Several of the studies does further emphasise the need for changes in the collaboration between actors as an important step towards circular transition in the PV industry. Based on this, it can be derived that there is a limited focus on circular strategies and circular value chains and how these contribute to a circular transition of the PV industry.

Challenges

The articles further emphasise some of the challenges regarding the EoL of PV panels. These challenges have been categorised and systematised. The result of this categorisation is shown in figure 1.13

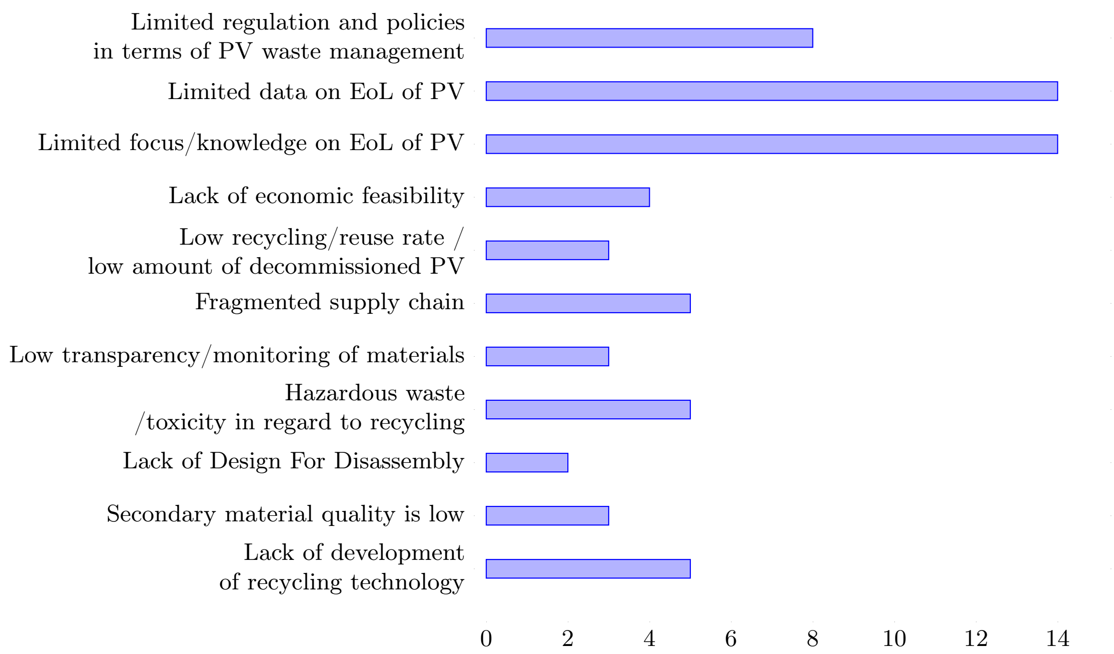


Figure 1.13. Identified challenges in terms of EoL of PV panels

The most general challenges mentioned in the articles are limited data on the EoL of PV and limited focus and knowledge regarding this phase. The limited data is due to the lack of availability of primary data on the amount of PV waste generated and the waste management hereof. Several of the LCA studies use secondary data and mention that this creates uncertainty in the results. An LCA study conducted by Tian et al. [2021] investigates perovskite PV panels but due to limited data on these PV panels, the study includes data from another type of PV panels. Santoyo-Castelazo et al. [2021] emphasises the importance of more accurate primary data for the life cycle inventory (LCI).

Additionally, 14 of the articles mention limited focus and knowledge on EoL of PV as a challenge. This is also associated with the limited amount of data. A study conducted by Liu et al. [2021] argues that the lack of knowledge is due to limited availability for recovery and reuse. Several other studies also emphasise that this is due to the limited knowledge on the network for recycling and the information on waste streams and management hereof. This is also shown in the literature review conducted by Seo et al. [2021] as the recycling processes are modeled in the LCA based on either pilot scale, literature-based or lab scale.

It is deemed relevant to zoom in on the LCA studies. This is done to systematise the approach of the LCA conducted in the studies which will both serve as inspiration for this study' LCA and will furthermore contribute to an understanding of the existing LCA studies and how/where this study can contribute with knowledge.

Out of the 24 articles, 15 are LCA studies. However, the LCA studies have various approaches in terms of PV type, functional unit, LCA method and type, and lifespan which will be elaborated on in the following. For a description of the different terms associated with LCA see section 3.3.

Functional unit
Table 1.1 shows that there has been used a variety of different functional units (FU).

Functional unit	Total number
1 kg PV waste	2
1 m^2 of PV module	2
Unit of electricity produced	1
24 tons of PV module waste	1
1000 kg EoL PV panels	1
1 kWh of electricity of produced electricity	4
Multiple (based on literature review)	2
NA	2

Table 1.1. Functional unit used in the identified LCA studies

The category *"Multiple"* covers different FU that has been identified in literature reviews by Santoyo-Castelazo et al. [2021] and Seo et al. [2021]. In the study by Santoyo-Castelazo et al. [2021] the most common functional unit is 1 kWh whereas for the study by Seo et al. [2021] there is no pattern. The majority of the LCA studies compare different waste scenarios. However, the different functional units make it difficult to compare the LCA studies to each other. The studies furthermore calculate the LCA with different lifetimes on the PV panels. The most common lifetime used is 20-30 years. A study by Murphy and McDonnell [2017] also states that there is a broad variety in the results due to the use of different assumptions and methods.

LCA method
LCA studies can either be conducted as attributional or consequential. The LCA studies identified have however limited mentioning of the used method and approach. Only Duflou et al. [2018], Ansanelli et al. [2021], and Lunardi et al. [2018a] use the attributional approach. None of the other studies describe which approach they use. This makes the LCA less transparent which further entails that comparison between the different LCA studies is difficult. Additionally, there have not been conducted any consequential LCA studies on EoL of PV panels.

1.4.1 Knowledge gaps

Through the literature review, several knowledge gaps have been identified. This study seeks to build upon the existing knowledge by investigating these knowledge gaps. In general, there is a limited amount of LCA studies that include the EoL phase. Additionally, the majority of the included studies investigate recycling in terms of EoL of PV panels which is why knowledge of how waste management at the higher levels of the waste hierarchy affects the environmental performance of a PV panel is limited. This combined with the limited studies which include CE actively in the research further emphasises that the field of CE in the PV industry is limited. Therefore, this study will further the knowledge in this field by conducting an LCA focusing on the higher levels of the waste hierarchy in the EoL phase of a PV panels. Additionally, this study will explore CE in the PV industry to contribute with knowledge on how CE affects waste management and the environmental performance. Since there were not found any consequential LCA studies, conducting a consequential LCA on PV panels will contribute with information to the research field. Finally, none of the studies investigates the topic in a danish context which is why this may entail different results and is therefore relevant to investigate.

2 Research question and design

This chapter introduces the research question that will be addressed in the study. In addition, sub-questions are included to support answering the research question. Subsequently, the research design of this study is presented which serves as the framework for the investigation. This includes a description of how the sub-questions, applied methods, and conceptual framework help to answer the main research question.

2.1 Research question

This study seeks to build upon the existing knowledge about PV panels by investigating some of the knowledge gaps that have been identified. Based on the accumulated knowledge from the previous chapter 1, it can be deduced that; the PV industry is growing which entails a new challenge at the EoL for the PV panels. Waste management is relatively new in the industry, but the waste generation will only increase in the coming years. This highlights a need for an increased focus on waste management for the PV panels. The main focus in the industry regarding waste management is recovery and recycling. Further, the majority of the conducted studies within the field of EoL also have recycling as the primary focus. This entails a lack of studies concerning waste management at the higher levels of the waste hierarchy. Additionally, there is limited focus on the implementation of CE in the PV industry. Therefore, this study investigates EoL at the higher levels of the waste hierarchy and thereby contribute to the transition towards CE. Additionally, this study is conducted from a Danish perspective since none of the identified studies investigates the topic within a danish context. This may entail different results and is therefore relevant to investigate further. To investigate the topic of EoL management the following main research question will be used:

What are the environmental impacts of recycling and reuse of photovoltaic panels and how can further reuse be supported by actors involved in the end-of-life management from a Danish perspective?

This study compares recycling and reuse. However, the main focus throughout the study is reuse. The reasoning behind the increased focus on reuse is because recycling is a part of the current waste management practice with a functional framework to handle recycling through the WEEE Directive. Furthermore, reuse ranks higher in the waste hierarchy and further contributes to supporting the transition to CE since it keeps the PV panels in circulation with a greater value than with the use of the recycling approach. Additionally, the WEEE Directive also mentions prepare for reuse as an important aspect of waste management.

The following sub-questions are created in order to answer the main research question:

2.1.1 Sub-questions

- How is the current waste management of PV panels?
- What is the environmental performance of recycling and reuse of a c-Si PV panel quantified by a life cycle assessment?
- How can the circular strategy; slow support realising CE in the PV industry?

To answer the aforementioned sub-questions, a research design has been conducted to support the investigation of the main research question. The research design will include the purpose, method, and approach behind the different sub-questions.

2.2 Research Design

The research design is the plan for conducting the research of this report [Creswell, 2009]. It creates the framework for the analysis of the EoL management for PV panels and is used to answer the main research question. Figure 2.1 below illustrates the applied research design used to conduct this report and how the sub-questions contribute to answering the main research question.

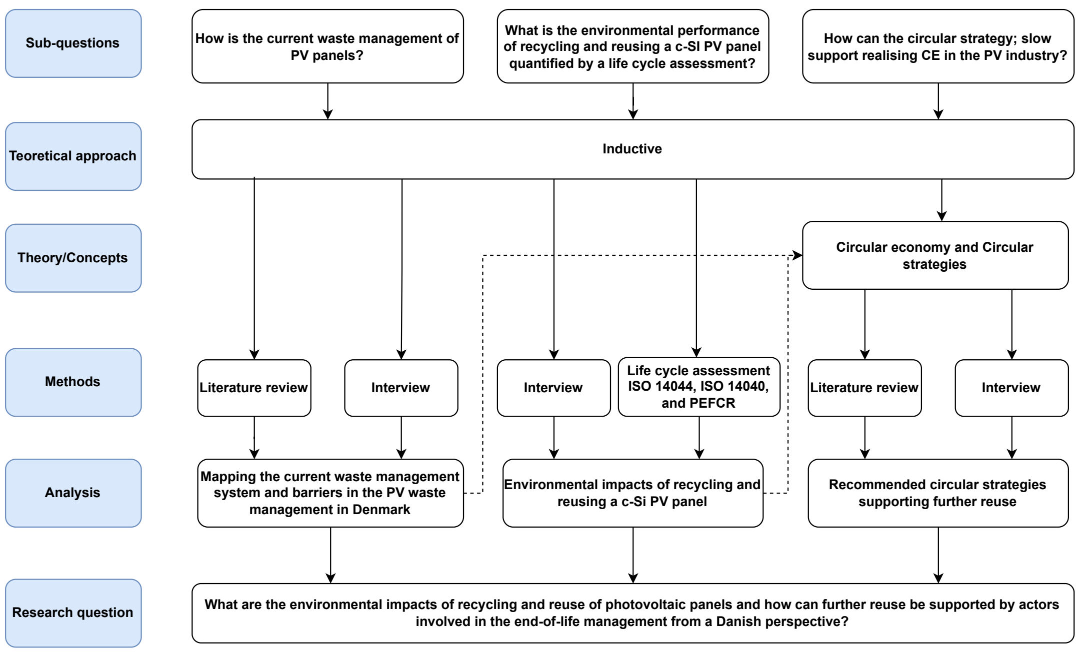


Figure 2.1. Visualisation of the research design. The chart shows the research process from how the sub-questions support answering the research question. The dotted lines indicate that analysis results from the two first sub-questions are used to answer the third sub-questions.

The research approach is the theoretical interpretation of the collected data. The research approach used in this study has mainly been inductive. The inductive research study is based on empirical data that is used to explore a phenomenon and identify themes or patterns. This approach has been used in this report to draw conclusions, make assumptions and generalisations based on the observations that have been made through interviews, literature, and the conducted LCA [Brooks, 2013]. Further, empirically collected data has been compared with the theoretical literature for the purpose of investigating whether the investigated or observed can be interpreted from a theoretical framework. This means that the inductive research approach used in this report attempts to make general conclusions based on specific collected empirical data [Brooks, 2013].

The next part of the research design is the methods and conceptual framework that have been applied to answer the sub-questions. This study employs a combination of quantitative and qualitative approaches to answer the main research question. This is done to strengthen both the quantitative and qualitative research performed through this study since the research field is complex and therefore beneficial to include both perspectives. The mixed-method approach contributes to broader insight and an expanded understanding of the topic Creswell [2009]. In this study, the use of mixed methods has entailed that the statement from interviews have been used as data for the conducted LCA. Moreover, the LCA results combined with statements from the interviews and the literature have enabled proposing of relevant recommendations for the PV industry that are based on both qualitative and quantitative data. Followed by the methods is the analysis, which highlights the results of each sub-question and how the outcomes for each sub-question are collected and contribute to answering the main research question.

The first sub-question *How is the current waste management of PV panels?* is answered using literature search and interviews as the methods. Literature search has been used to gain a broader understanding of waste management and the relevant actors in a danish perspective. The literature searches are supplemented with interviews with relevant actors in the EoL management of PV panels to achieve a practical understanding of their role in the waste management system for PV panels as well as the experienced barriers. The identification of the barriers will help to get an understanding of what hampers the current waste management of recycling and the development of reuse within the EoL phase.

The second sub-question *What is the environmental performance of recycling and reuse of a c-SI PV panel quantified by a life cycle assessment?* is answered through a conducted LCA of a c-Si panel to estimate the environmental impacts of recycling and reusing these. The focus on the PV panel type c-Si is because this is the most dominant type used worldwide and in the literature and will continue to be used in the future. The LCA is conducted based on data from the Ecoinvent database, literature, and assumption based on the conducted interviews.

The last sub-question *How can the circular strategy; slow support realising CE in the PV industry?* will have its starting point in the conceptual framework *Circular Strategies* by Konietzko et al. [2020b] with the focus on the strategy *slow*. Further, this sub-question will use the results and observations from the previously investigated sub-questions. Based on the conducted interviews and the use of literature, it is possible to formulate circular principles and recommendations that can support the PV industry with EoL management of PV panels and the transition to CE.

3 Methods

The purpose of this chapter is to present the research methods used in this study. Therefore, a literature review is presented as this has been used to conduct the state-of-the-art (SOTA) analysis. Furthermore, the method interview is included to obtain empirical data from the involved actors. Finally, a description of life cycle assessment (LCA) is introduced. A short description of the different methods and how these are applied in the research of this study are included.

3.1 Literature review

This section includes a description of literature review which have been used to conduct the SOTA analysis presented in section 1.4.

Literature review is a method to identify and collect existing research and knowledge within the investigated field and uncover gaps in the research field [Snyder, 2019]. The method has been included to justify the relevance of this study and to uncover knowledge gaps in the research field. Snyder [2019] distinguishes between three different approaches (systematic review, semi-systematic review, and integrative review) to conducting a literature review. The systematic review synthesises literature in a structured way based on a specific question which makes it easy to reproduce the results of the search. Systematic reviews are often considered statistical where the methodological approach in the literature needs to be comparable as the aim is to deduce similarities and differences in the studies [Snyder, 2019]. The semi-systematic reviews are more suitable for literature that uses different conceptualisations, and methods and where the field is investigated by different research groups as this makes it difficult to use the statistical approach. The semi-systematic review aims to synthesise knowledge gaps and identify gaps for further research [Snyder, 2019]. The integrative review aims to synthesise a research field to create new theoretical approaches and reconceptualise [Snyder, 2019]. This literature review can mainly be considered a semi-structured review. The reasoning behind this is, that the research is done by various research groups within diverse disciplines, who work with different methods and purposes which makes it difficult to have a systematic approach. Therefore, it is necessary to interpret and analyse the literature (e.g. in terms of the challenges) to uncover common issues [Snyder, 2019]. This review is considered semi-systematic as it allows for a thematic analysis of the research in order to derive general patterns.

Additionally, Snyder [2019] suggests to following four steps in order to conduct a literature review which are *Step 1: design, Step 2: conduct, Step 3: analysis, and Step 4: structuring and writing the review.* The construction of the literature review is inspired by these four steps.

Step 1: Design
The first step concerns the design of the literature review. This includes the search strategy including search string, search criteria, inclusion and exclusion criteria, and databases [Snyder, 2019].

Initially, two literature reviews on the end-of-life of PV panels were reviewed. These have been used as inspiration to locate keywords which have been included in the search string. Conducting the search string was an iterative process where different constellations of keywords and screening criteria were tried out to find the most suitable keywords and ensure relevant studies were uncovered. In the first search strings *photovoltaic**, *PV*, and *"solar cell*"* were included in *"all fields"*. However, this search resulted in various articles that focused on other technologies (e.g. batteries, hard-disk, diodes etc.) where PV panels were included as a secondary subject in the research. To narrow down the articles to exclusively focus on PV panels, the keywords *photovoltaic*, *PV*, and *"solar cell*"* were set as an inclusion criteria in the *"title"*, as shown in table 3.1. Furthermore, *"end-of-life"* was included in the search string in *"all fields"*. This was done to ensure that the research within the EoL phase was identified as this is the subject of this study. The keyword *"end-of-life"* was deemed suitable to cover the different types of waste management (recycle, reuse, disposal etc.). Furthermore, this term was deemed relevant in order to avoid the use of *"waste"* as there is a risk of excluding CE by using this. Subsequently, terms related to LCA were included in *"all fields"* to ensure that relevant research was found on LCA where the EoL phase was included in the scope. Here, *"environmental impact*"* was deemed relevant as an alternative wording to LCA. The search string was combined by using *"AND"* between the search fields. This further helped to narrow down the search as this criterion defines that the articles must include a combination of keywords from the three search fields.

The scientific database that has been used for the review is *PRIMO*. PRIMO is a consortium of different libraries including Aalborg University Library and collects sources from various databases (e.g. Web of Science and Science Direct) [Løvschall et al., 2008]. The reasoning for using PRIMO is, therefore, that it enables access to sources from different scientific databases and gathers these which makes the search scope wider. However, this does also have some disadvantages as the search does not exclusively search in journals that are specific to the research field. The literature review has been limited to only including literature from the past five years. This limitation has been done to include the newest research in the field. Furthermore, as the focus on waste management of PV panels is new [Sica et al., 2018], a limitation of five years is deemed relevant. Only peer-reviewed articles have been included in order to ensure that the highest international literature in the field has been identified.

Table 3.1 summaries the search string.

Search field	Search criteria
Title	photovoltaic* OR PV OR "solar cell*"
All fields 1	"end-of-life"
All fields 2	LCA OR "Environmental impact*" OR "life cycle assessment*"
Year	2017-2022
Language	English
Status of journal	Peer-reviewed

Table 3.1. Search string. * is used to search for various suffixes and "" is used to lock the key words in the search

Step 2: Conducting the review

Step 2 relates to the selection of relevant articles that have been included in the final literature review [Snyder, 2019]. The search string yielded 231 articles. The strategy for selecting the relevant articles is based on a screening approach. Figure 3.1 shows the different screening criteria, that have been included in the review. The first screening criteria was based on a read-through of the titles to sort out articles that were not deemed relevant. Here, titles that did not include either of the search terms in table 3.1 or terms that are associated with the research field (e.g. waste, recycling, reuse, circular) were excluded. This resulted in a total of 51 articles. The abstracts were then read and checked for relevance in terms of the research field which yielded 29 articles. Here, some of the articles were excluded due to focus on a niche area e.g. a specific part of the PV panel such as the back sheet. Finally, the full articles were reviewed and five articles were sorted out due to focus on waste estimations. Based on these criteria, the review yielded a total of 24 articles.

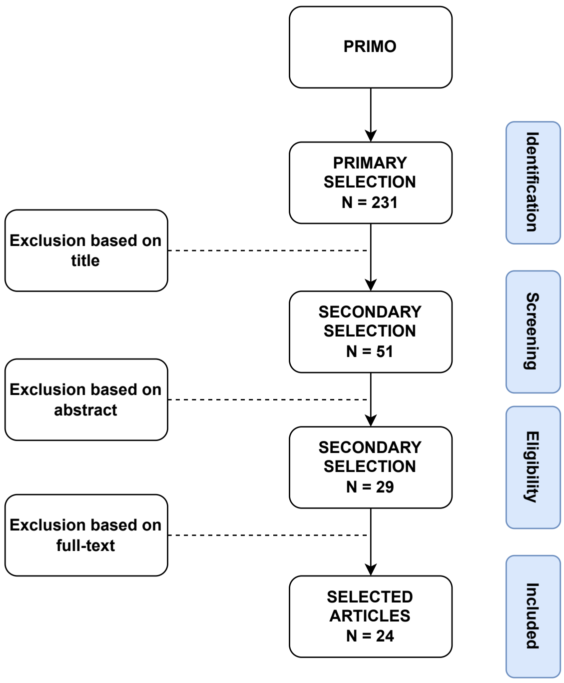


Figure 3.1. Screening criteria throughout the literature search inspired by [Moher et al., 2009]

Step 3: Analysing the literature
Step 3 revolves around the approach to analysing the literature [Snyder, 2019]. The analysis of the articles is based on thematisation and characterisation of the articles. Here, the articles were divided into title, year, country, type of PV technology, topic, waste management types, challenges, and future work/knowledge gaps. Additionally, the challenges were noted down while reading through the articles and finally structured in general categories in order to systematise the results. For the articles that focused on LCA, further characterisation was done in the categories: LCA method, lifetime, and functional unit. These characterisations enable comparison of the different articles and identifying general patterns in the literature which is the basis of the SOTA analysis.

Step 4: Structuring and writing the review
Finally, step 4 entails deducing the findings of the literature review and writing it [Snyder, 2019]. The result of the analysis is the foundation for writing the SOTA, presented in section 1.4. From the characterisations, different patterns in the literature have been derived which allowed identifying knowledge gaps in the literature. Furthermore, this emphasised the need for future research in the field. The knowledge gaps serve as a justification for this paper's research field as this paper seeks to contribute with new aspects within this knowledge gap.

3.2 Interview

This section includes a description of the method; interview which has been used throughout the report to support answering the main research question as well as the sub-questions.

Interview is a qualitative method for collecting empirical data. The purpose of conducting interviews as a part of the data collecting is the advantage of getting a deeper understanding and a broader perspective on the phenomenon being investigated based on the respondents' point of view [Brinkmann and Tanggaard, 2015].

There are no standard rules or procedures for conducting research interviews. However, there are different choices of methods in the stages of an interview investigation. Kvale and Brinkmann [2009] describe seven overall stages of conducting an interview which is presented in the following and further used to describe how interviews in this report have been used.

- Thematising: Formulate the purpose of the investigation prior to the interviews being carried out. This means that the why and what of the investigation should be clarified beforehand.
- Designing: Plan the design of the study where all seven stages of the investigation are taken into consideration. The purpose of designing is to ensure that the indented knowledge is obtained through the interviews.
- Interviewing: The interviews should be conducted based on an interview guide.
- Transcribing: This stage has the purpose of preparing the obtained knowledge from the interviews for analysis with a transcription from the oral speech to written text.
- Analysing: Decide, which modes of analysis are relevant for the conducted interviews based on the purpose and the topic of investigation.

- Verifying: This stage has the purpose of ascertaining the validity, reliability, and generalisability of the interview findings. This means investigating how consistent the results are (reliability) and whether the interview study investigates the intended (validity).
- Reporting: The final stage is about communicating the findings of the study and the applied methods.

These different stages have been used to guide the conducted research interviews in this study, and further ensured a correct use of the results from the interviews.

Besides the different stages, the interviews can also be conducted using three overall interview types; The structured, the semi-structured and the unstructured interview. The interview type that is used in this report is primarily the semi-structured interview. When using this type, the questions are prepared beforehand and are used to guide the interview to achieve the intended information from the respondent used in the interview study. However, the questions are not necessarily asked in a particular order to follow the flow of the interview which allows deviation from the interview guide [Hua, 2015]. The semi-structured interview is a useful tool to explore a general research area to obtain new knowledge and perspectives. Further, it is especially useful in the initial research stages as it provides an informative direction for further research [Hua, 2015].

In this report, seven interviews have been conducted to support the answering of the main research question. The aim of each interview is described in table 3.2. Before conducting the above-mentioned interviews an agenda and, if needed, specific questions were sent to the respondent to prepare them in the best possible way for the interview. To conduct the interviews with different actors in the PV industry, snowballing has been used through the interviews to find some of the respondents used in this study. Additionally, all the interviews were held online through Microsoft teams due to both geographies and convenience.

Table 3.2. Interviews conducted for the project

Respondent	Aim of interview	Type of Actor
Sebastian Hornbeak Sustainable design engineer at Ennogie Date: 16/03 2022 Duration: 42 minutes	To gain insight into: - Ennogie's role in the PV industry - Ennogie's refurb concept of PV panels - Ennogie's network - Barriers and potentials	Importer of roof-mounted panels New and reused panels
Theiss Stenstrøm Director Power to X at Better Energy Date: 13/04 2022 Duration: 40 minutes	To gain insight into: -Better Energy's role in the PV industry - How Better Energy work with reuse and recycling - Barriers and potentials	Developer of solar farms New panels
Bertrand Lempkowicz PR, Marketing & Communication Manager at PV Cycle Date: 17/03 2022 Duration: 35 minutes	To gain insight into: - PV Cycle's role in the PV industry - General knowledge about EoL processes of PV panels - The EU context - Barriers and potentials	Collective scheme organisation
Torben Frahm Managing Director at European Recycling Platform (ERP) Date: 31/03 2022 Duration: 42 minutes	To gain insight into: - ERP's role in the PV industry - Extended producer responsibility - Barriers and potentials	Collective scheme organisation
Morten Harboe-Jepsen Managing Director at Elretur Date: 08/04 2022 Duration: 40 minutes	To gain insight into: - ERP's role in the PV industry - Extended producer responsibility - Barriers and potentials	Collective scheme organisation
Massimo Forti Managing Director at Ragn-Sells Date: 5/04 2022 Duration: 32 minutes	To gain insight into: - How Ragn-Sells work with reuse and recycling - EoL supply chain of PV panels - Barriers and potentials	Waste operator
Flemming Vejby Kristensen Chairman of the Danish PV Association Date: 28/04 2022 Duration: 45 minutes	To gain insight into: - The Danish PV industry - Extended producer responsibility - Barriers and potentials	Trade association

To understand the contexts of the conducted interview a short description of each actor is presented.

Ennogie was established in 2010, but it was not until 2017 that they started selling PV roof-mounted panels. Besides the PV panels, they are providing everything needed for a complete roofing product. They are developing, producing, and selling the PV roof-mounted panels [Hornbeak, 2022]. Further, the company has started to investigate the business case of reusing and refurbishing used PV panels in their PV roof-mounted panels. However, it is not a fixed part of the company yet as they have only purchased used PV panels one-time [Hornbeak, 2022].

Better Energy is a renewable energy company that creates new green energy by developing solar farms with new PV panels. Better Energy has existed since 2012 and is building solar farms in Denmark, Sweden, Finland and Poland. They have recently switched technology to glass-glass since these absorb sunlight from both sides which means that the glare from the earth is used too. Further, these panels are effective and easier to recycle. This technology is their standard today and this will be applied to solar farms in the future. Currently, only one farm applies this technology and the rest of their farms use the old technology, which does not absorb sunlight from both sides [Stenstrøm, 2022].

PV Cycle is a non-profit association that offers both collective and tailor-made waste management and legal compliance services. The association was founded in 2007 by the PV industry. However, PV Cycle today includes a broad range of electrical and electronic equipment, batteries, packaging, and industrial waste in its portfolio [PV Cycle, 2022]. They offer their service all around the world. Additionally, they are pushing for the development of the legislation about PV recycling and reuse in an EU context and are trying to educate the best with the budget that they have [Lempkowicz, 2022].

European Recycling Platform (ERP) Denmark has existed since 2009 and is a collective scheme. ERP are placed all over Europe with small branches and consist of approximately 400 people. The danish branch only consists of two employees. ERP provides solutions that cover the extended producer responsibility for WEEE, batteries, and packaging recycling. There are four companies in Denmark which are a part of the collective waste schemes. ERP Denmark has a market share of 7-8% with their 120 customers [Frahm, 2022].

Elretur is the biggest collective scheme in Denmark and provides, just as ERP, solutions that cover the producer's responsibility for WEEE and batteries for their 950 members. They have a market share of approximately 80%. Further, Elretur was founded in 2005 and is a non-profit organisation only handling the private part of the PV waste, which includes PV panels collected from the Danish recycling sites [Harboe-Jepsen, 2022].

Ragn-Sells is a Swedish established waste operator and one of the biggest waste operators in Scandinavian. In Denmark, they have specialised in four fractions: electronics, cardboard and paper, plastic and food waste. Ragn-Sells collaborates with four out of the five danish collective schemes. In the past 4-5 years they collaborated with ERP and gathered electronics waste on behalf of them. Ragn-Sells is one of the operators in Denmark that collects fraction 6 where photovoltaic panels are included [Forti, 2022].

The Danish Solar Cell Association is a trade association for actors within the PV industry. They have 35 members which include manufacturers of components for the PV industry and importers of PV panels. The association aims to support initiatives that increase the development of PV panels and facilitate communication with policymakers [Kristensen, 2022].

Processing of the interviews

After the thematising, designing, and interviewing the interviews for the different respondents, the results from the interviews needed to be processed. The next stage, based on the seven stages by Kvale and Brinkmann [2009], is transcribing the interviews.

The interviews were recorded to ensure the use of the results from the interviews in the report. Afterwards, the interviews were transcribed in the language in which the interview was conducted. The transcriptions were used to create an overview of the results obtained from the interviews.

The next stage is analysing. All the interviews were coded into subjects related to the sub-questions or different topics of investigation. The coding was done through an iterative process where new topics arose while analysing the interviews. This coding entailed a better overview of the relevant points in relation to a specific topic. Further, the sixth stage is verifying. This stage is supported by sending the used quotes or references to the respondent for approval to ascertain the correct use and understanding of the respondents' statements. Further, the tables from section 5.2 were also sent for verification since some of the barriers were derived indirectly from the interviews. Additionally, the respondents were also questioned in relation to changes or additions. This allowed the respondent to reconsider or add to their points or statements. However, no major revisions were made and all the used citations and quotes were approved by the different respondents.

The final step is reporting where the interviews and the different statements from the respondents were used to support and shape the analysis mainly for the first and third sub-questions. However, the interviews have also been used for some of the assumptions made in the conducted LCA. The interviews have been used both for quoting directly and as references.

3.3 Life cycle assessment

This section elaborates upon the LCA approach. This includes a general description of LCA, the structure of conducting this, and the aim hereof. Therefore, this section will serve as the foundation for answering the second sub-questions, presented in section 2.1.1.

Life cycle assessment is a tool to quantify the environmental impacts of a product throughout its whole lifetime from cradle-to-grave or from cradle-to-cradle. This enables the different life cycle stages to be included in the assessment which overall is the extraction of raw materials, processing of these, production, usage, and EoL treatment [Matthews et al., 2015]. The EoL treatment includes different waste management such as reusing, remanufacturing, recovery and disposal. LCA consists of the input (i.g. raw materials, electricity demand for production) and the output (emissions to air, products created, waste etc.) [Matthews et al., 2015]. LCA can be used to analyse hotspots or/and to compare the environmental performance of different products or different scenarios. The hotspot analysis is helpful to identify the stages of a product which has the most significant contribution to the environmental impacts of the product. Whereas, the comparison analysis allows to compare the environmental performance of e.g. different waste management scenarios of a product or to compare different products to each other. LCA can be used for decision-making as it predicts the potential environmental impacts of a product and thereby can provide information to the decision making processes. LCA cannot predict the actual environmental impact due to uncertainties in the modelling [International Organization for Standardization, 2006a].

There exists an LCA standard that sets the framework for conducting an LCA which is acknowledged globally [Matthews et al., 2015]. The standards are ISO 14040 and ISO 14044. ISO 14040 includes the principles of conducting an LCA [International Organization for Standardization, 2006a] whereas ISO 14044 engages in the guidelines and requirements [International Organization for Standardization, 2006b]. According to ISO 14040, the LCA composes of four steps; definition of goal and scope, inventory analysis, impacts assessment, and interpretation of the results [International Organization for Standardization, 2006a]. A description of these steps are elaborated upon the in following based on ISO 14040 [International Organization for Standardization, 2006a] if not cited otherwise.

Step 1: Goal and scope
The goal and scope include a description of the purpose of the LCA and the methodological approach. Therefore, this step considers the investigated product and its system boundaries which contains the activities of the products. Here, limitations and assumptions are also elaborated upon. The step furthermore engages in the functional unit which is the reference point for the LCA. The inputs and outputs are referenced according to the functional unit [International Organization for Standardization, 2006b].

Step 2: Inventory Analysis (LCI)
This step encompasses data for the LCA. Here, a distinction is made between fore- and background data. The foreground data is the collected data which accounts for the inputs and outputs of the respective product. Whereas the background data is based on data from general databases such as EcoInvent. This is an iterative process where more data may be needed to meet the goal of the study. It may also be relevant to include assumptions when data is missing. This can also lead to a revisit of the goal and scope. This step also considers the by-production and the modelling thereof. The by-production is the process that creates other outputs simultaneously with the output related to the investigated product. There exist different ways of modelling this depending on the type of approaches used in the LCA. The attributional approach allocates the co-product whereas the consequential approach models a substitution of the production of the by-product on the marked. Therefore, by using the consequential approach the production of by-products is avoided [Weidema et al., 2018]. The reasoning behind this is, that the consequential uses the marginal approach which includes the whole production that can be affected by the marked. In opposition, the attributional uses the average approach where the marked is fixed which is why there are no changes regardless of the change in output [Weidema et al., 2018].

Step 3: Impact assessment (LCIA)
The third step is the assessment and evaluation of the LCI results and potential environmental impacts. This step furthermore includes organising the results into different categories and characterisation in order to interpret the results. It is mandatory to use classification and characterisation according to ISO 14040 [International Organization for Standardization, 2006a]. In the classification, the inventory results are sorted according to relevant impact categories e.g. global warming. Characterisation is where the classified categories are multiplied by the characterisation factor. This is done as not all the environmental impacts affect the impact categories equally. Furthermore, it is optional to use normalisation and weighting as additional steps to interpret the results. In normalisation, the different impact categories are assigned to a common reference. By weighting the LCIA results it is possible to compare the impacts categories in order to

determine which of these categories have the most severe impacts. The LCIA results are multiplied by a common weighting factor. However, weighting is the most subjective approach to evaluate the results [Matthews et al., 2015].

Step 4: Interpretation
The final step is where the results are interpreted and reported. Here, a summary of the results from the investigation is presented. Communicating the LCA results to the intended audience should be transparent by presenting the included data, used methods, assumptions, limitations, and uncertainties. Additionally, sensitivity analysis can be conducted where different input, output, and methods are modelled to shed light upon how these affect the LCA [Matthews et al., 2015]. This step may also include recommendations for the intended audience based on the LCA results.

Besides the ISO 14040 and ISO 14044, this study engages in the industry-specific guidelines from the *Product Environmental Footprint Category Rules (PEFCR) for Photovoltaic modules used in photovoltaic power systems for electricity generation.* PEF aims to provide detailed and comprehensive guidance for the technical aspects of how to conduct a PEF study [European Commission, 2020]. This study is using the PEFCR for PV panels to guide and structure the LCA. The use of PEFCR in a consequential approach, as this study applies, is possible since PEF also acknowledge the ISO 14040 and ISO 14044 standards in which allocation should be avoided and substitution prioritised.

3.3.1 Framework conditions for the conducted LCA

This study seeks to investigate two different EoL scenarios for PV panels; recycling and reuse. Therefore, the LCA is conducted as a comparative LCA in order to engage in the environmental performance of these scenarios and compare the differences hereof. This contributes to supporting decisions regarding which of the EoL treatments that have the lowest environmental impacts. The following present the two scenarios of this LCA study.

Recycling scenario: This scenario is based on the WEEE Directive where the recycling rate follows the target of a minimum 85% recovery and 80% recycling. Therefore, this scenario acts as baseline for the comparison. This scenario will work with different recycling rates for each fractions based on Li et al. [2018] and Urbina [2022]. In this scenario, the decommissioned panels are transported from Denmark to Germany and Belgium after 30 years of use. Here, the PV panels go through mechanical and metal processing. These processes require energy which is included. The exact recycling rates, transportation, and energy usage are described in section 6.3 which includes assumptions for the LCA.

Reuse scenario: In the reuse scenario the lifespan of the PV panel is prolonged by an additional 15 years. Urbina [2022] suggests that the lifespan of PV panels can be extended by 10-20 years. Therefore, the assumption of 15 years is deemed relevant as this is the average hereof. In this scenario, the PV panels are taken down after 30 years of use and are resold on the reuse market. This entails that the panels are washed and tested [Hornbeak, 2022] before being used for additional 15 years. In this scenario, repair of the panels is included. The assumption is that 10% of the panels need repairing. Furthermore, this scenario includes that the PV panels are transported from Germany to Ennogie in Denmark.

Furthermore, as described in section 1.4, there are limited consequential LCA studies within the field of EoL treatment of PV panels. Therefore, this study engages in a consequential LCA to contribute to the research field. It is further deemed relevant in order to assess the consequences of either choosing recycling or reusing PV panels which contribute to the decision making processes.

Based on conclusions from the European Commission's Product Environmental Footprint (PEF) the life cycle modules and stages defined in the EN standard 15804 are considered to be the most suitable standardised reference point [Dodd et al., 2019]. Therefore, these life cycle modules and stages are used to define the stages for the studied product system in this LCA. The life cycle modules and stages used to conduct this report's LCA are illustrated in figure 3.2.

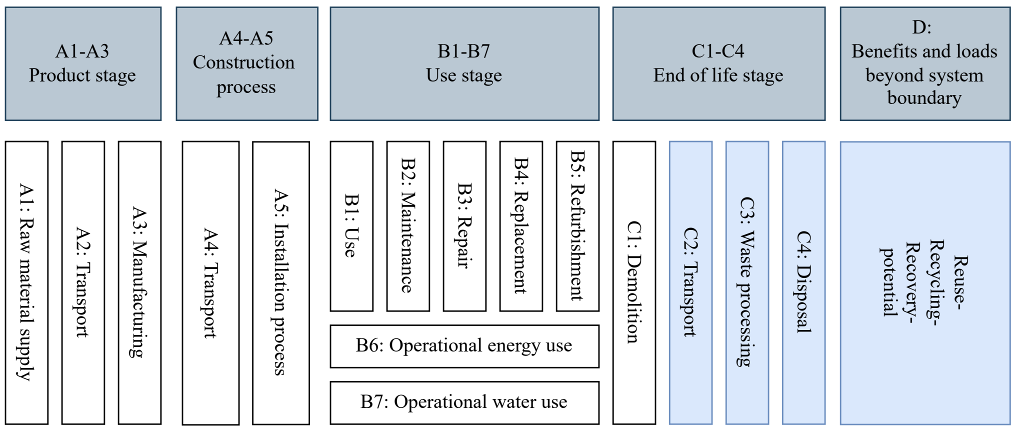


Figure 3.2. Own illustration of life cycle stages with inspiration from DS [2019]. The life cycle stages C2-C4 and D, which are included in this study are marked in blue.

The illustrated life cycle stages are based on the standard EN 15804:2019, which serves as core product category rules for construction products and are further also used on EPDs on PV panels. As illustrated in figure 3.2 this study includes the EoL stages (C2-C4), and the stages for the benefits/loads beyond the system boundary (D). The reason for including these stages is that this project investigates the circular scenarios after the service life of a c-Si panel. Additionally, the reason why A1-A5, B, and C1 are not included in the system boundaries is based on the assumption that these processes are the same in the investigated scenarios throughout the 30 years. These stages can therefore be omitted from the product system of this LCA.

4 Conceptual framework

This chapter presents two approaches to the concept of CE. Firstly, the concept by EMF [2015] is presented as this includes the most acknowledged definition [Kirchherr et al., 2017]. Additionally, the tool *Circular Strategies* by Konietzko et al. [2020b] as this suggests approaches to operationalise CE.

4.1 Ellen MacArthur

This section introduces the concept of circular economy presented by EMF [2015]. As mentioned in the introduction, see section 1.3, Ellen MacArthur deals with the cradle-to-cradle perspective in two different cycles; technical and biological. Since this study investigates PV panels, the technical cycle will exclusively be included, as described in section 1.3. Within the CE different strategies for closing the loops are presented; maintenance, reuse/redistribute, refurbish/remanufacture, and recycle, see figure 4.1.

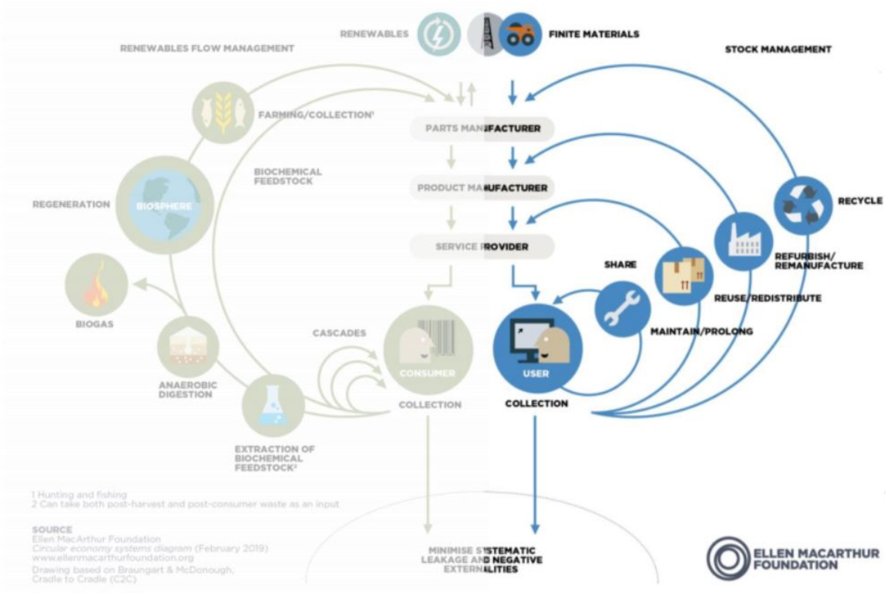


Figure 4.1. The Butterfly model - The technical and biological cycles by EMF [2015]. The biological cycles is faded to illustrate that this is outside of the scope of this study.

In the circular strategies, the aim is to keep the loops as tight as possible. By keeping the loops as tight as possible fewer processes (service provider, product manufacturer, and parts manufacturer) are needed in the process which entails that fewer materials and lesser energy will be used. Therefore, the strategies in the inner circles should be prioritised prior to the strategies in the outer circles. The inner circles seek to prolong the lifetime of the product [EMF, 2015] which then reduces the environmental impact [Bundgaard, 2016]. EMF [2021] have developed a glossary to get common definitions of the terms:

- **Maintenance:** "Keep a product in its existing state of quality, functionally and/or cosmetically, to guard against failure or decline. It is a practice that retains the highest value of a product by extending its use period."
- **Reuse:** "The repeated use of a product or component for its intended purpose without significant modification. *Small adjustments and cleaning of the component or product may be necessary to prepare for the next use.*"
- **Redistribute:** "Divert a product from its intended market to another customer so it is used at high value instead of becoming waste."
- **Refurbish:** "Return a product to good working order. This can include repairing or replacing components, updating specifications, and improving cosmetic appearance."
- **Remanufacturing:** "Re-engineer products and components to as-new condition with the same, or improved, level of performance as a newly manufactured one. *Remanufactured products or components are typically provided with a warranty that is equivalent to or better than that of the newly manufactured product.*"
- **Recycling:** "Transform a product or component into its basic materials or substances and reprocessing them into new materials. *Embedded energy and value are lost in the process. In a circular economy, recycling is the last resort action.*"

However, based on these definitions it can be derived that it is margins that differentiate the inner circles. As the concept of CE is fairly new it is, therefore, a challenge when the term *reuse* is used as this may cover several of the inner circles. This was further emphasised in the SOTA, see section 1.4, as EoL terms infrequently are used interchangeably. This paper uses the definition of reuse/redistribute and recycling according to EMF [2021]. The scenarios for the LCA, as presented in section 3.3.1, are based on these definitions. The CE concept by EMF [2015] can be operationalised through *Circular Strategies* by Konietzko et al. [2020b] which is described in the following section.

4.2 Circular strategies

In order to answer the third sub-question presented in section 2.1, it is deemed relevant to include the concept of *Circular Strategies* presented by Konietzko et al. [2020b]. As this study seeks to further reuse of PV panels, this concept is included as a way of operationalising the strategy of *reuse* presented by EMF [2015]. The strategies narrow, slow, and close have previously been proposed in research and are therefore not new [Konietzko et al., 2020b]. Konietzko et al. [2020b] expand the general circular approach by adding two new dimensions; regenerate and inform. Figure 4.2 illustrates the circular flow among the strategies.

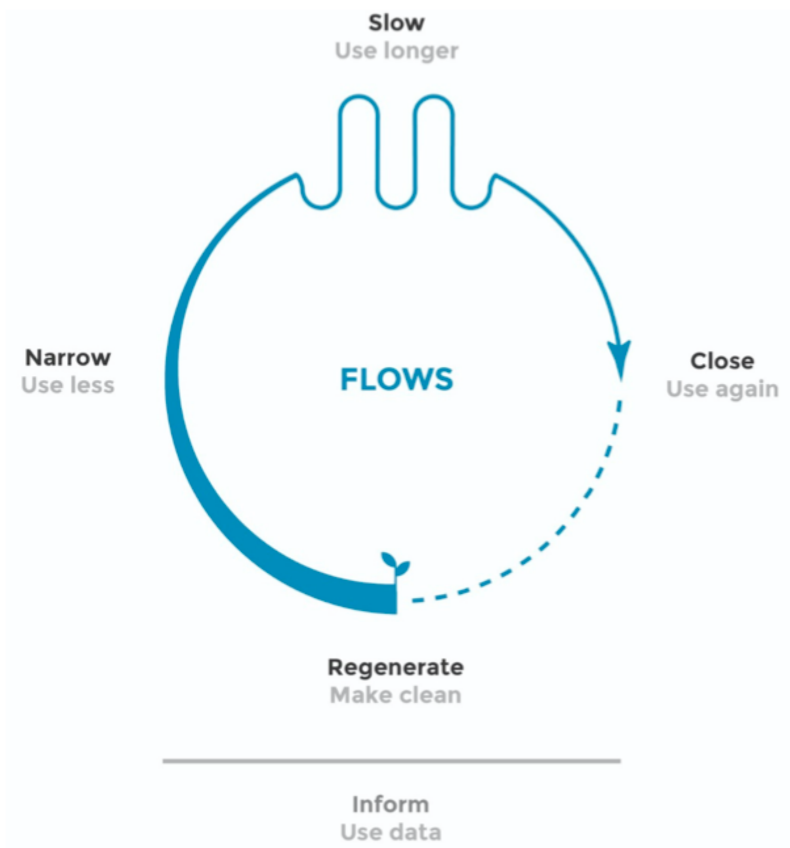


Figure 4.2. Circular strategies: narrow, slow, close, regenerate and inform material and energy flows.

The blue line indicates the key strategies and the inform strategy is indicated by the grey line as a support strategy. *Narrow* concerns using fewer materials and energy (i.g. design for multiple purposes), *Slow* means that the lifespan of a product is prolonged (i.g. design for easy repair of the product).*Close* is when the materials avoid ending up as waste and instead they are used again (i.g. design with recycled materials). *Regenerate* is an addition that has been made to include the perspective of the purity of the materials and energy and strives to achieve a cleaner production through the use of non-toxic materials and renewable energy (i.g. design with non-toxic or living materials), which are important aspects to incorporate in CE. Therefore, the use of solar energy will be an important element in the transition to CE. *Inform* is illustrated outside of the circular flow as this acts as a support strategy to the aforementioned circular strategies. This strategy is added as different studies state that information is essential in the transition towards CE. The inform strategy is not a final goal but should be included in the strategies continuously.

4.2.1 Innovation principles

Konietzko et al. [2020b] introduce that each strategy can be operationalised at different levels through different innovation principles; *Product*, *Business model*, and *Ecosystem*. The three principles deviate in their focus as the product perspective exclusively concerns the design of a product, the business model broadens the perspective and suggests circular and sustainable solutions within the business model canvas such as product-as-a-service, and the ecosystem perspective goes beyond the local business model perspective. Generally, the focus in the literature has been limited to the product and business model and therefore neglected the ecosystem perspective [Konietzko et al., 2020b]. Therefore, the focus has mainly been limited to the firm/organisation. Here, Konietzko et al. [2020b] argues that in order to achieve the transition towards CE, it is essential to consider the actor-network and interaction among the actors and therefore the whole ecosystem perspective. The ecosystem perspective is characterised by Konietzko et al. [2020b];

- "consist of multiple locally, regionally or globally distributed entities that do not belong to a single organisation"
- "involve dynamic, collaborative and competitive relationships"
- "imply flows of data, services, and money"
- "often involve complementary products, services, and capabilities"
- "evolve as actors constantly redefine their capabilities and relations to others"

The ecosystem perspective, therefore, includes different actors (e.g. producers, suppliers, developers, operators, end-users, organisations, etc.) that participate in the network and contribute to the same desired outcome [Konietzko et al., 2020b]. The inclusion of these actors entails that their business models are also considered in the development of circular strategies. The ecosystem perspective aims at re-positioning the actors and thereby changing their internal relations. Figure 4.3 visualise the connection between the different innovation principles.

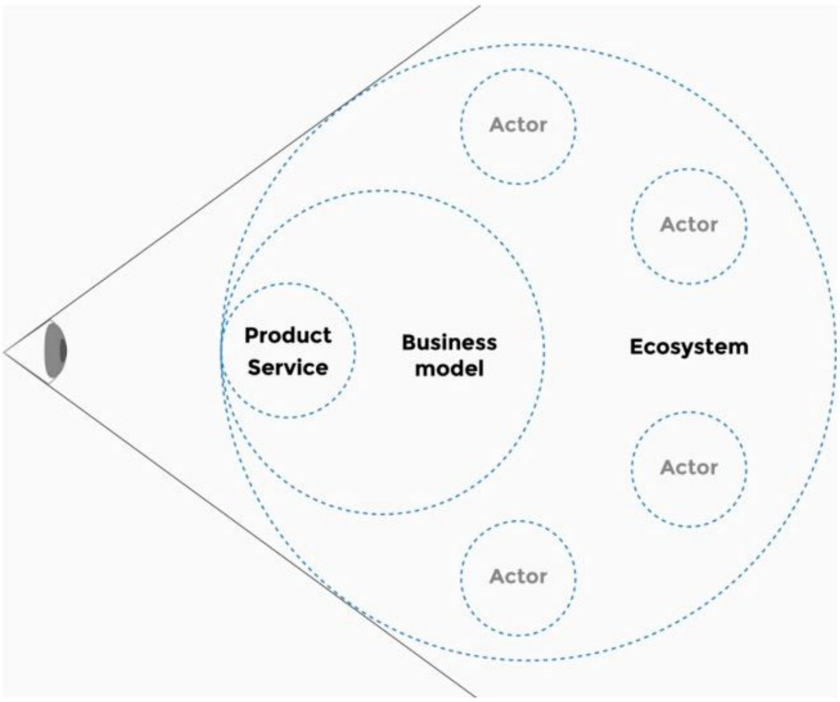


Figure 4.3. Ecosystem perspective of the three innovation principles

4.2.2 Circularity Deck

Konietzko et al. [2020b] suggest the use of *Circularity Deck* which is a practitioner-focused tool designed to analyse the circular potential of a business and subsequently develop circular innovation strategies. The Circularity Deck arises from the circular strategies and the innovation principles and presents different constellations of these which act as inspiration in terms of the transition towards CE. Therefore, this tool suggests different circular strategies within each innovation principle. These are presented on a deck of cards and in different combinations, they aim at "better ecosystems". However, it is still important to assess the environmental impacts of the chosen strategies Konietzko et al. [2020b].

4.2.3 Realising circular economy

As presented in section 2.1, this study investigates the environmental performance of recycling and reuse of PV panels. Furthermore, the study seeks to further reuse of PV panels. Therefore, it is deemed relevant to examine the overlap between the circular terms presented by EMF [2015] and Konietzko et al. [2020b]. Here, the three inner circles; maintenance, reuse and refurbish are within the circular strategy *slow*. The reasoning behind this is, that these three circles prolong the lifetime of products by repairing or switching out components. In the last circle; recycling is within the strategy *close* as the materials are reprocessed and enter into the material flow again. Thereby, the material flows stay closed as the extraction of virgin materials is avoided. Figure 4.4 illustrates the overlaps between the two concepts.

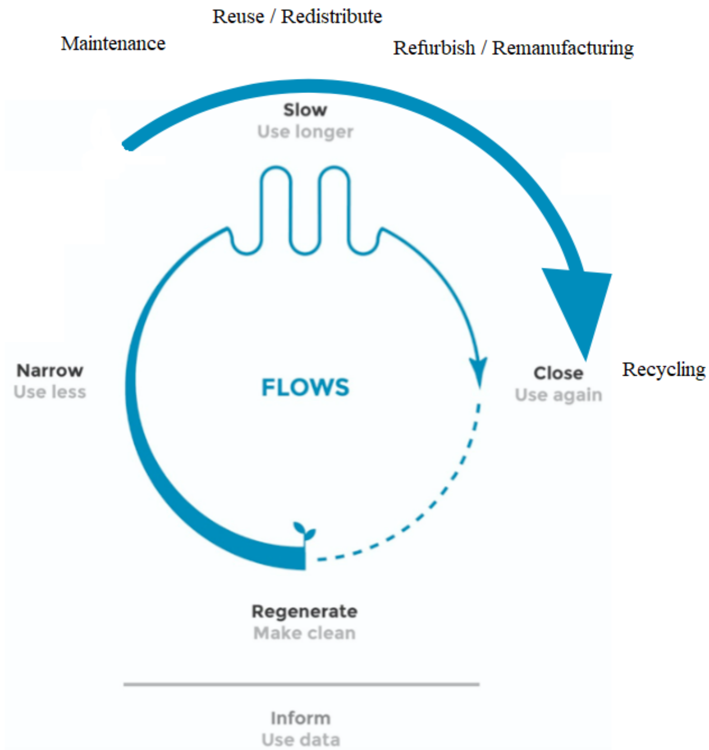


Figure 4.4. Combination of the Bufferfly Model by EMF [2015] and the Circular Strategies by Konietzko et al. [2020b]

As presented in section 1.2.1, the WEEE Directive regulates the waste management of PV panels. This does mainly focus on recycling and recovery and neglects targets within direct reuse of EEE as it only mentions prepare for reuse. This means that the current waste management of PV panels is located in the outer circle under recycling. This is further emphasised in the SOTA, see section 1.4, as the majority of the literature focus on recycling. Additionally, through interviews with the respondents, the focus through the supply chain of EoL treatment of PV panels is on recycling.

This paper will contribute with knowledge in terms of furthering reuse by suggesting recommendations based on circular strategies within the slow strategy. Due to the current waste management and focus on recycling, recommendations for recycling will not be investigated further. The circularity deck by Konietzko et al. [2020b] will serve as a guiding tool for developing circular strategies for the PV industry. As reuse is within the slow strategy according to figure 4.4, the slow strategy is the foundation for developing circular strategies in this study. The approach for developing circular strategies for the PV industry takes departure in the results from the LCA, see chapter 6, and the barriers pointed out by the respondents, see section 5.2. Furthermore, the identified barriers contribute to aspects that hamper the current opportunities for reusing PV panels. The development of the circular strategies takes departure in the barriers in order to accommodate these in the different innovation principles; product, business model, and ecosystem.

5 Current waste management of photovoltaic panels in Denmark

To answer the first sub-question, see section 2.1.1, this chapter presents and seeks to understand the waste management of PV panels in Denmark. This includes an understanding of the different actors involved in the waste management and their role as well as an understanding of the different barriers the PV industry faces regarding the waste management.

5.1 Waste management and its actors

It is, as described in section 4.2, important to look at the actors as increased collaboration is essential in the transition to CE. Therefore, this section focus on the relevant actors and their role in the waste management of PV panels to understand the current waste management system. The waste management system of WEEE is a socio-technical system with interactions between actors and technology to achieve a certain purpose. The system consists of different actors with different interests. The criteria for selecting the actors used in this investigation are based on Zacho et al. [2018]. The criterion is that the actors should be involved in the current WEEE system for PV panels and thereby have a stake in the system. However, the Danish PV Association has also been included even though they are not directly involved in the current WEEE system. The reasoning behind this is that the association has a wide interface with several actors in the PV industry.

The description of the actors and their role is following the life cycle stages of the PV panels from import to EoL with a focus on recycling and reuse, as illustrated in figure 5.1. Processes associated with the use phase (building process, operation and maintenance, and dismantling) are outside the scope of this study. However, a short description of these processes is included in the section to understand the life cycle of PV panels.

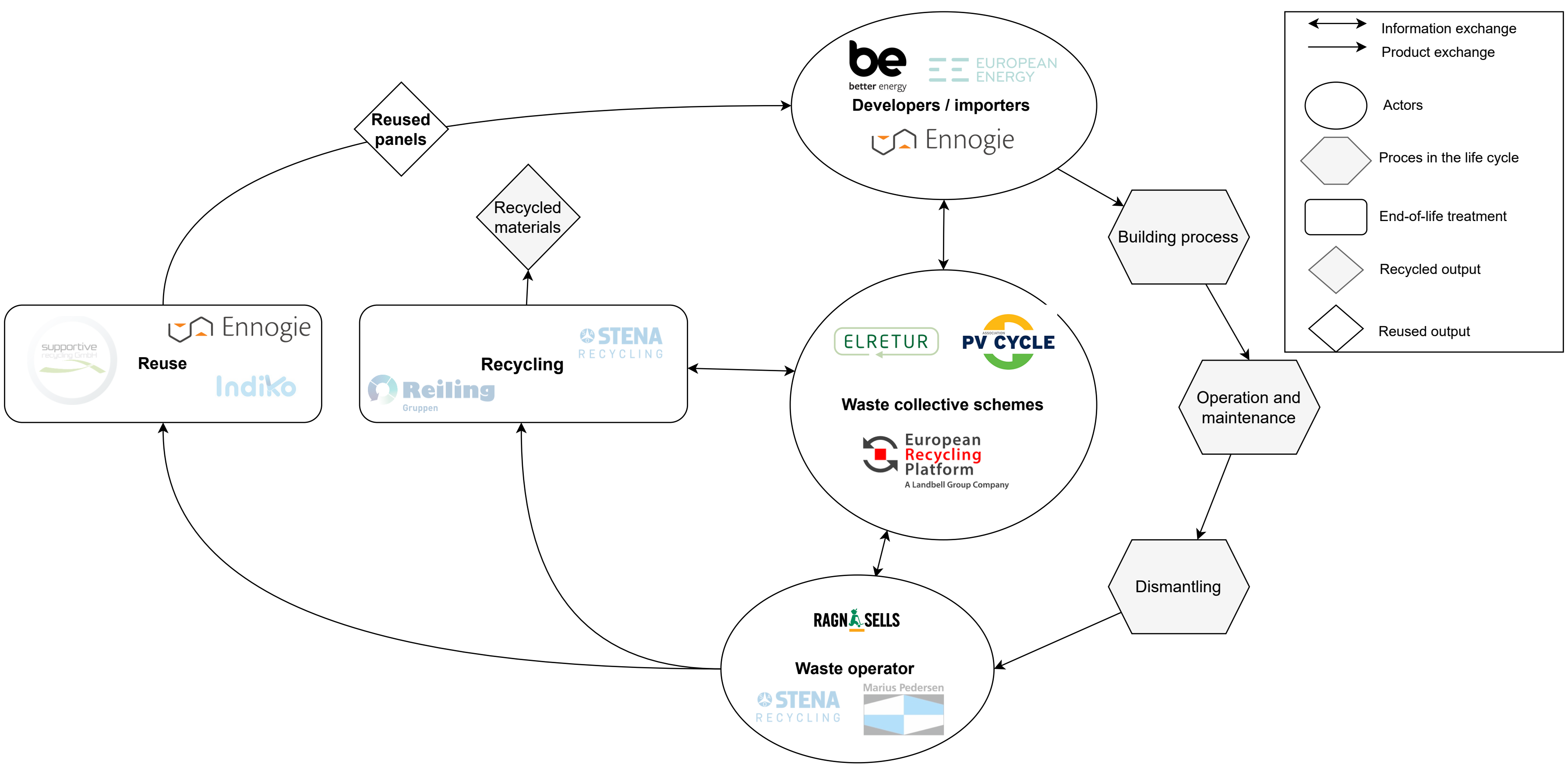


Figure 5.1. Flowdiagram of PV panels including actors, processes, and end-of-life treatment. Due to the focus in this study of the end-of-life phase, processes associated with the use phase (building process, operation and maintenance, and dismantling) are not included which is why these are visualised as grey boxes This is also the case for "recycled output". Additionally, actors that are mentioned during interviews but have not been interviewed are transparent.

5.1.1 Production

The first step in the life cycle of PV panels is the production stage. This stage is outside the scope of this study and is therefore not included in the figure 5.1. However, the production phase is deemed relevant to describe to obtain a general understanding of the life cycle of PV panels prior to EoL. It is estimated that approximately 90% of the manufacturers are placed in China [Lempkowicz, 2022]. The companies in Denmark who import the PV panels can to a certain degree have an influence on which components are used in the PV panels [Hornbeak, 2022]. As mentioned in section 1.1 there are two types of PV panels ground panels and roof panels. The ground panels are the most used and according to Stenstrøm [2022] approximately 90% of the panels on the market in 2021 are Better Energy's as they established the largest solar farm in Denmark in 2021 [Stenstrøm, 2022].

5.1.2 Developers and importers - Import into the Danish market

Before the PV panels can enter and be used on the European market, the developers and importers of PV panels are, as described in section 1.2.1, obliged to register in the national producers register e.g. the quantities of the marketed products. This is necessary since the developers and importers are responsible for the product throughout its lifetime. This entails financing and organising take-back schemes and waste treatment of the product. In Denmark, DPA is responsible for the Danish Digital Register of producers. The developers and importers can choose to handle the task themself or to transfer parts of the tasks associated with producer responsibility to established collective schemes [DPA, 2022b]. The collective schemes offer and perform the administrative and practical tasks for a fee or based on a membership scheme [DPA, 2022b]. In practice, almost no importers of EEE, in general, have taken individual responsibility [Zacho et al., 2018].

An important differentiation regarding the PV panels is whether they are business-to-business (B2B) or business-to-consumer (B2C).

Within **B2B** there are different business models that the developers are working with. Overall, there are two approaches the Divestment and the Power Purchase Agreements (PPA) approach. With the use of divestment the developers divest the farms to investors but keep operating the farms. This business model is used by the developer European Energy [European Energy, 2022a]. In the PPA long term supply contracts are made with businesses which ensure delivery of renewable energy. In this business model the developer keep ownership and sell green energy. Both, the companies European Energy and Better Energy are examples of companies that uses this business model [Stenstrøm, 2022; European Energy, 2022b].

B2C is opposite when companies are selling to consumers. The company Ennogie is an example of a B2C company. Ennogie is selling its product to private households and private businesses [Hornbeak, 2022].

Additionally, there has been a switch in 2021 to include ground panels as household waste if they have low voltage, which is not further defined [Harboe-Jepsen, 2022]. However, this distinction can be difficult for the developers since they cannot get an unambiguously answer to where they belong as ground-mounted panel developers [Stenstrøm, 2022].

5.1.3 Building processes

As described in chapter 1, it is estimated that approximately 80% of the PV waste will consist of panels with premature failures from e.g. the transportation and installations rather than panels that have reached EoL. This indicates that the building process is also an important life cycle stage to focus on in regards to waste management of PV panels.

5.1.4 Operation and maintenance

Chapter 1 describes that 2/3 of the waste panels may be possible to repair or refurbish, which highlights the need for an increased focus on the operation and maintenance to prevent generating waste before the panels have reached their EoL. Additionally, Stenstrøm [2022] argues that the climate in Denmark is advantageous for the PV panels in regards to the efficiency due to the lower temperatures compared with South Europe and the wind is cooling the panels. This can entail that the efficiency of the panels after 30 years is still around 80% since the climate does not wear and tear on the panels the same way as in countries with more extreme weather [Stenstrøm, 2022]. Therefore, the panels can potentially have a lifespan beyond the 25-35 years in Denmark [Kristensen, 2022].

5.1.5 Dismantling

This life cycle stage affects the ability to reuse or refurbish the PV panels rather than recycle them. Hornbeak [2022] states based on Ennogie's experiences, that the dismantling process on the received used PV panels influenced the reusability. The way the cables were cut and how the panels were managed subsequently e.g. transportation affected the discard rate. Hornbeak [2022] further states, that Ennogie would like to control the process of dismantling the PV panels more next time they buy used PV panels to decrease the discard rate.

5.1.6 Waste management

The current amount of PV panel waste in Denmark is, as highlighted in chapter 1, very small since the installation of PV panels started a little later than in other European countries [Lempkowicz, 2022]. Further, the waste amounts are estimated to remain at this level until 2030. However, the waste generated from the PV panels is still important to treat properly. Therefore, this section will describe how the PV panel waste is collected and further treated either as recycling or reuse.

Waste collection

The waste collection can overall be handled by the developers and importers themselves or through collective schemes. This section will focus on the different collective schemes and their role. It is based on interviews with the Danish collective schemes Elretur and ERP Denmark and the European collective scheme PV cycle. Further the interviews are supported by literature.

In Denmark, the DPA system calculates the amount of WEEE waste that the collective schemes must collect from the municipal collection points or recycling sites. The practical execution is collectively referred to as the "allocation scheme" where chosen operators are managing the WEEE waste from the collection points. The DPA system is an annual allocation scheme with an allocation period of 12 month which runs from September 1 to August 31. The allocation scheme establishes which collection points and factions have been allocated to the individual actors, as described in section 1.2.1, including the geographical distribution of municipalities [DPA, 2021]. The allocation scheme only manages the private generated waste which ends at the recycling sites [Harboe-Jepsen, 2022; Frahm, 2022].

Further, each of the collective schemes has an operator connected, who is responsible for the collection at the allocated recycling sites. The operators can work across the different collective schemes. For instance, the operator Ragn-Sells is working directly with three out of four collective schemes in Denmark and indirectly with the last one. The collective scheme LWF is not included as they are only managing light sources [Forti, 2022]. Further, the collective schemes can also have different operators based on geographics. The operators are chosen based on tenders and the contacts are typically 3-5 years [Harboe-Jepsen, 2022]. Additionally, it is important for both Elretur and ERP Denmark that it is a collaboration with the operators with a focus that goes beyond the lowest price [Frahm, 2022]. It is important that there are few shifts in operators to ensure stability in terms of waste management [DPA, 2021].

Besides the national collective schemes, it is also possible for the developers and importers to use other collective schemes of their choice. Better Energy is using the non-for-profit organisation PV Cycle which operates all around Europe and in countries where there is no national scheme for the collection [Lempkowicz, 2022].

Recycling

The current waste management of PV panels is mainly performed through recycling processes. Denmark has no end-processing facilities for PV panels and only a few pre-processing facilities for WEEE in general [Zacho et al., 2018]. Therefore, the Danish collected PV waste is shipped to the nearest recycling plant in e.g. Germany and Belgium [Frahm, 2022; Harboe-Jepsen, 2022]. The current small amounts of PV panel waste entails that the panels are stored at different facilities in Denmark until the amount is suitable for transportation either alone or with other EEE fractions [Harboe-Jepsen, 2022; Frahm, 2022]. There has been no interviews with a recycler, thus this section is based on literature and the interview with PV Cycle.

Figure 5.2 illustrates a simplified recycling process for c-Si PV panels and the general processes are described below.

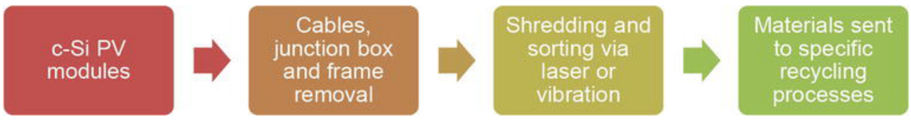


Figure 5.2. PV Cycle recycling process for c-Si panels by Lunardi et al. [2018b]

The first step in the recycling process of PV panels is deframing, where the aluminium frame is removed from the panel. The frame only consists of aluminium, which is easy to recycle. The next step is removing the junction box, which consists of plastic and cables with cobber. After the removal of the frame, junction box, and cables, the panels are shredded, sorted, and separated [Lunardi et al., 2018b]. In figure 5.3 the fractions from the shredding process are shown. There are different sorting machines for this process. The main processes are the use of magnets, vibration, blowing, and optical sorting. The separation of the materials allows them to be shipped to specific recycling processes associated with each extracted material. Finally, the recycler will sell the different fractions based on the best prices. There are several different methods available on the market for recycling PV panels, but the aforementioned is illustrating the overall process [Lunardi et al., 2018b].

Figure 5.3. Material fraction after the recycling process [Lempkowicz, 2022]

The extracted materials will most likely not be used in the production of PV panels but in other sectors instead. Lempkowicz [2022] from PV Cycle states that the extracted materials technically can be used in the PV industry. However, this is not the case today as the majority of the manufacturers are located in China. The geographical distance does not make it economically or environmentally logical to ship it back. Further, Lempkowicz [2022] highlights that the extracted materials are needed in Europe as well in other industries.

Reuse

As described in chapter 1, the market for reuse is new both in Europe and in Denmark. There are not a lot of companies engaged in the reuse market. This section is therefore based on one concrete example of a company that has investigated and worked with reuse in Denmark.

The small and medium-sized company Ennogie has started exploring reuse of PV panels. The company has sold reused PV panels, but so far, they have only bought one batch of 4620 panels from one solar farm in Germany. The process of reusing PV panels is first and foremost to find reusable PV panels. In the case of Ennogie the used PV panels needed to fit with the measurements of the roof panels that they sell to incorporate the reused panels directly into their existing product. The used panels were bought through an auction and subsequently shipped to Denmark. However, the discard rate of the used PV panels was high. Approximately 1/3 of the panels were not reusable due to poor management of the panels in the dismantling and transportation processes. Furthermore, to resell the used PV panels, they need to go through a process of cleaning and testing the function and capacity of the panels which also leads to a small degree of disposal. For the processes of cleaning, testing, and collection sequences, Ennogie has used the company Indiko to perform these. Today, Ennogie has sold all the reused panels and is currently only offering new panels as their integrated roof panels. Most of them are sold to a German architectural firm that will use them in construction of a sustainable building. However, the reused panels have also been sold in the Danish B2C market [Hornbeak, 2022].

Besides Ennogie, the German recycling company, Supportive, has also started to investigate the possibility to reuse PV panels. Supportive collaboration with ERP Denmark and Ragn-Sells regarding reuse of PV panels. However, the amount of PV panels that have been reused is still too small to say something general or draw any conclusions [Forti, 2022].

5.2 Barriers in waste treatment

This section presents the barriers in regards to recycling and reuse of PV panels which are highlighted during interviews with different actors involved in the EoL of PV panels. This is deemed relevant to answer the first sub-question and subsequently identify how these barriers affect the current waste treatment.

The following sections are based on interviews with; Ennogie (importer), Better Energy (developer), PV Cycle (collective schemes), ERP (collective schemes), Elretur (collective schemes), Ragn-Sells (operator), and the Danish PV Association (trade association). These interviews are included to obtain various perspectives on barriers in regard to recycling and reuse. Table 5.1 and 5.2 take departure in the barriers identified in the literature, see section 1.4. However, barriers from the literature that are not mentioned by the respondents are not included in these tables. Furthermore, the table 5.1 is expanded with an additional aspect the respondents deemed as a barrier.

5.2.1 Recycling

This section presents the barriers related to the recycling of PV panels. Table 5.1 summarises the barriers in regard to recycling of PV panels.

Barriers	**PV Cycle**	**Ennogie**	**ERP**	**Ragn-Sells**	**Elretur**	**Better Energy**	**the Danish PV Association**
Limited regulation and policies in terms of PV waste management					X		
Limited focus/knowledge on recycling of PV		X			X	X	
Lack of economic feasibility	X		X	X			
Low amount of decommissioned PV	X			X	X	X	X
Lack of development of recycling technology					X	X	X
Fragmented supply chain						X	
Low transparency/monitoring of materials						X	
Limited responsibility in term of EPR			X				

Table 5.1. Summary of barriers related to recycling of PV panels. Barriers noted in italics are identified through the interviews

Limited regulation and policies in terms of PV waste management

Harboe-Jepsen [2022] stresses that the lack of national focus and endorsement regarding the waste treatment of PV panels is a barrier. Further, it contradicts the general desire to increase the development of PV panels. Harboe-Jepsen [2022] requests responsibility from the authority as they want the green energy produced by PV farm to increase but does not consider proper waste treatment of these. Harboe-Jepsen [2022] points to this as a barrier as the authorities do not prioritise reserving money to finance the waste treatment and research waste treatment technologies of PV panels.

Limited focus/knowledge on recycling of PV

Several of the actors agree that there is a limited focus and experience with the EoL treatment of PV panels. Hornbeak [2022] elaborates:

> *"It is a huge problem in terms of how the EoL treatment of the PV panels should be handled - it has not become a problem yet due to the low amounts. However, it will become in the coming years.*

Forti [2022] does also emphasise this as an issue as the current small amounts of decommissioned PV limit the research within EoL treatment of PV panels. This is also acknowledged by Stenstrøm [2022], as he describes the limited focus and knowledge as *"a loophole due to the lack of clarity regarding decommissioned PV panels"*. Furthermore, it is unclear how the large PV farms should be taken down at EoL [Stenstrøm, 2022]. This emphasises the lack of focus and knowledge which is deemed as a challenge across the actors, from developer to waste operator.

Lack of economic feasibility

Lempkowicz [2022] points to the barrier of costs associated with recycling. However, this barrier is related to the waste treatment of PV panels outside of the EU and thereby outside the scope of the WEEE Directive. Lempkowicz [2022] gives an example and explains that when PV Cycle participates in fairs around the world and gives presentations, they are often met with skepticism. The developers consider the collective schemes as expensive and that it is difficult to get the developers to own up to their responsibility when there is no legislation.

Another aspect of the economic feasibility is the treatment facilities. Today, the danish PV waste is shipped to Germany and Belgium. Frahm [2022] explains that the current recycling requirements entail a need for investments in recycling facilities and these investments are high. Further, Forti [2022] participated in a project that investigated whether it was feasible to invest in the treatment facilities of PV panels. However, due to the limited amount on the danish market, it is currently not profitable to invest in technologies in Denmark [Forti, 2022]. Despite this, Stenstrøm [2022] presumes that *"there will be a financial incentive to recycle it"* when the larger PV farms reach their EoL.

Low amounts of decommissioned PV panels

The low amount of decommissioned PV panels does affect the economic feasibility of recycling PV panels and the development of recycling technologies. The economic costs are associated with the little amount that needs to be collected. Harboe-Jepsen [2022] further explains:

"PV panels are a great example since there are small amounts and we, therefore, have not developed the technology yet. We can tell there is a bigger potential. However, today we cannot separate the panels without it being extremely expensive.".

In this regard, Harboe-Jepsen [2022] explains that in 2021 they collected 30 tons of PV waste distributed in the 98 municipalities which leaves a limited amount for each municipality. This increases the collection costs as the transportation costs are divided out on small amounts of PV waste across Denmark. Both Forti [2022] and PV Cycle [2022] agree that the current low amounts causes high costs in terms of collection and transportation of PV panels for recycling.

Lack of development of recycling technology

Stenstrøm [2022] and Harboe-Jepsen [2022] both mention the current recycling technology as a concern. Here, Stenstrøm [2022] is sceptical of the current recycling technology, as this includes shredding the whole panel and separating the material fractions afterward. Stenstrøm [2022] emphasises the uncertainty regarding the recycling technology as a barrier and elaborates: *"We have not optimised the processes, so we can utilise all the materials"*. The separation of the materials is also a concern to Kristensen [2022], as he mentions that the panels are put together thoroughly which makes it difficult to separate the materials.

Kristensen [2022] points to the Encapsulant made out of EVA which is difficult to separate from the glass. This, therefore, compose a challenge in recycling. Better Energy has changed the design of the PV panels with an eye to recycling [Stenstrøm, 2022]. This change includes that the back sheet, which is normally made out of plastic, is substituted with glass which leaves the plastic in the panels to be avoided [Stenstrøm, 2022]. Their reason for making this substitution is, that it is more efficient as the PV panels can generate electricity from the back sheet as well. Furthermore, Stenstrøm [2022] explains that it is easier to separate and recycle glass properly. In this regard, Harboe-Jepsen [2022] explains that the optimal technology for waste treatment of PV panels has not yet been developed and commercialised as the panels have generally not entered into the waste stream yet. Forti [2022] argues that: *"The quantities of PV waste do not exist in Denmark, so it is currently not possible to develop technological solutions (rd. for recycling) in Denmark"*. Therefore, the current amount is shipped to Germany [Kristensen, 2022].

Fragmented supply chain and low transparency

Stenstrøm [2022] explains that the fragmented supply chain regarding recycling of PV panels does become a barrier as it is difficult to know exactly how the PV panels are recycled. This is due to the shift in actors handling the waste which makes it challenging to follow the tranche of the PV panels. This further contributes to the barrier *Low transparency*. Stenstrøm [2022] does therefore question the current waste treatment and whether or not this is done in the most environmentally friendly way.

While mapping the actors in the supply chain presented in section 5.1, the fragmented supply chain as a barrier was further exemplified. In the initial search of identifying relevant actors to interview for this project, it was derived that some actors were unsure of the whole supply chain. Furthermore, incorrect redirection to several actors that did not work with PV panels occurred.

Extended producer responsibility

Frahm [2022] emphasises the extended producer responsibility as a main barrier. Frahm [2022] explains that there are two issues in this regard. Generally, there is a lack of acknowledgement in terms of the responsibility in the PV industry as ERP often have to contact the PV developers to inform them about the EPR [Frahm, 2022]. Additionally, there exists "free-riders" which are importers and developers that do not own up to their responsibility. This means that they put products on the market that are covered by the WEEE Directive but do not consider the waste treatment of these products. This leaves the products on the market where the collective schemes, which are financed by other developers and importers, have to cover the costs associated with the waste treatment. Frahm [2022] explains that there are no fines or consequences for not taking this responsibility which he deems as a barrier.

5.2.2 Reuse

This section includes the barriers associated with the reuse of PV panels. Table 5.2 presents the barriers associated with reuse of PV panels.

Barriers	PV Cycle	Ennogie	ERP	Ragn-Sells	Elretur	Better Energy	the Danish PV Association
Limited regulation and policies in terms of PV waste management	X						
Limited focus/-knowledge on reuse of PV	X				X	X	X
Low amount of decommissioned PV	X	X	X	X	X	X	X
Lack of Design that further reuse		X			X		
Lack of economic feasibility		X	X				

Table 5.2. Summary of barriers related to reuse of PV panels.

Limited regulation and policies in terms of PV waste management

Section 1.2.1 presents the current legislation regarding PV waste management from which it can be derived that the WEEE Directive does not include targets that further reuse of PV panels. Furthermore, the requirements in the WEEE Directive are lost for reused PV panels [Urbina, 2022]. However, the Ecodesign Directive seeks to affect the design of the product for easier reuse. Lempkowicz [2022] points to the lack of respectively legislation and targets for reuse of PV panels as one of the main barriers. PV Cycle [2022] explains that the lack of legislation on reuse of PV panels hampers the development hereof. This entails that the market for reused panels today is "the far west" [Lempkowicz, 2022] where there are no standards for the quality of reused panels. This causes that reused panels of poor quality to be sold on the market for a high price [Lempkowicz, 2022]. Hornbeak [2022] argues that stricter regulation on how used PV panels should be handled can increase the focus on reuse and lead to new network constellations.

Limited focus and knowledge on reuse of PV

The limited focus and knowledge of reuse of PV panels is a barrier in terms of how to handle and reuse the panels on a greater scale and the quality of the reused panels. Stenstrøm [2022] points out that Better Energy is still in the preliminary phase of investigating reusing larger amounts of PV panels and how these should be taken down as this field is new to the industry. Stenstrøm [2022] estimates that there are at least 20 years until they need to take down their first farms. Additionally, they have not yet figured out how they will take down the PV farms for either recycling or reuse. Hornbeak [2022] explains that the limited focus and knowledge of reuse also becomes a barrier when it comes to handling the decommissioned PV panels. Hornbeak [2022] gives an example hereof, as they have bought one batch of used panels. However, due to the little experience with taking down the panels and safely shipping these, 1/3 of the panels were ruined during the shipment and had to be discarded. This, therefore, becomes a barrier as the PV panels are not handled safely for reuse. Both Lempkowicz [2022] and Harboe-Jepsen [2022] share their concerns regarding lack of focus on repair of PV panels. Harboe-Jepsen [2022] elaborates: *"No one has extracted a repair technology so they can sort them and bring them back to* *the market with warranty."*. This is also a concern that Lempkowicz [2022] shares, as he questions the quality of the reused panels that are sold on the market.

Low amounts of decommissioned PV panels

The majority of the respondents stress that the low amounts of decommissioned PV panels are the root of several of the other barriers. Harboe-Jepsen [2022] stresses that: *"you do not start by making a technology for the waste, you start by making a new product and then you put it on the market, and when it has become large enough as waste, then there are some who start to develop technologies to handle this"*. This explains that the current low amounts of decommissioned PV panels affect the development of technology and processes for reusing the panels. As mentioned, the low amount causes little experience with handling decommissioned PV panels for reuse purposes. Another aspect that Ennogie experiences regarding their business model of selling reused panels are the supply security of used panels [Hornbeak, 2022]. Here, Hornbeak [2022] explains *"we can not invest 100% in, for example, our refurb solution as we do not have a good source of used solar cells.* This is therefore challenging in terms of developing a business model that is dependent on the amount of decommissioned PV panels. This is an aspect that Harboe-Jepsen [2022] also finds critical in terms of reuse:

"The challenge with PV panels is that the amounts are so small. And when it comes to reusing, you have to have some kind of basic volume which we can not honor with the current amount of the PV panels".

This, therefore, limits the share of reused panels on the market as insurance of a basic volume of used PV panels is needed. This statement is supported by Frahm [2022] since ERP is currently collecting very small amounts of PV panels, which is not enough to create a basic volume.

Additionally, the low amount causes that the market for reused panels has not developed yet. The demand for reused panels is missing which limits the research and development of business models within the industry of reusing PV panels. Hornbeak [2022] explains that when Ennogie first started selling reused panels they were met with scepticism: *"At the beginning, it was a struggle as it is a new product (reused panels) and there were several concerns regarding the quality of the product"*. Ennogie had to be proactive to sell the reused panels on the market. The lack of market is also something Harboe-Jepsen [2022] recognises: *"There is simply no one who will buy them (ed. reused panels).*

Design that further reuse

Hornbeak [2022] stresses that the design of the panels and how they are put together makes it more difficult to dismantle these for reuse-purpose. Additionally, the panels need to be the same size and there needs to be a large number of panels for it to be profitable for Ennogie. This is currently a challenge for Ennogie, as the panels that are put on the market have different measures, and Ennogie requests specific measures for their reused panels [Hornbeak, 2022]. In this regard, Forti [2022] does also suggest that standard size for the PV panels could ease and make the reuse of these panels more efficient.

Lack of economic feasibility

Another barrier that Frahm [2022] states is the lack of economic incentive for reuse: *"There is a need for balance between reuse and the economy"*. If there is no demand for the reused PV panels with lower efficiency, specific size, etc., then they should be recycled instead. Currently, the knowledge regarding the economic aspects of reuse is not known or investigated since the market for reuse is, as described in chapter 1, informal and a nascent industry. Additionally, Hornbeak [2022] states, that due to the large discard rate Ennogie experienced, the costs could not be kept to a minimum. This entailed that Ennogie could not promote the reused panels as a cheaper option. Further, Hornbeak [2022], stressed that; *"The biggest incentive is the sustainability perspective on it"*. In connection with this Frahm [2022] argues that it is a better business case to reuse and sell the PV panels again than recycling which entails both economic and green incentives.

5.3 Sub-conclusion

In summary, this section has presented the current waste management of PV panels in a Danish context. Furthermore, barriers in terms of recycling and reusing PV panels have been identified. The current waste management is regulated by the WEEE Directive which entails that the developers and importers are responsible for financing waste treatment of PV panels due to the Extended Producer Responsibility. Here, the developers and importers can choose to do this through collective schemes that collaborate with different waste operators. Currently, the PV panels are either stored in Denmark or shipped to Germany or Belgium. The current waste management of PV panels does to a large extent mainly focus on recycling due to the regulation. Smaller actors have started to investigate the reuse of PV panels. Generally, the respondents agree that there need to investigate recycling and reuse of PV panels due to the increasing amounts of decommissioned panels in the coming 20 years. In the identification of barriers pointed out by the respondents, it was deduced that barriers found in the literature, see section 1.4, such as; lack of data, hazardous waste, and the quality of secondary materials, were not deemed as significant barriers in practice. Two of the barriers recurred through the supply chain for both recycling and reuse. These were; lack of focus and knowledge and low amount of decommissioned panels. It can be deduced that these two are the starting point for several of the other barriers. The barriers are intertwined and they, therefore, affect each other. By mapping the barriers, it was identified that there is more focus on the recycling of the PV panels as the respondents generally focused on barriers within recycling. Furthermore, various barriers were mentioned regarding recycling compared to reuse. From these results and the ones identified in the SOTA, see section 1.4, it can be derived that the industry for recycling of PV panels is far more advanced than reuse. Out of the involved actors, Ennogie has experienced practical barriers in terms of reuse as they are currently the only ones working with reused panels. Several of the respondents further mentioned that the development of reused panels is still new and unknown. This paper, therefore, seeks to contribute to the new field of reused PV panels. This is done by investigating the environmental performance of recycling and reuse of PV panels and suggesting initiatives within the circular strategy *slow*.

6 Life cycle assessment of recycling and reuse of a photovoltaic panel

This section answers the second sub-question, cf. section 2.1.1, by conducting an LCA for the scenario of recycling and reusing a c-Si PV panel. Firstly, the composition of a c-Si panel is elaborated upon to get an insight into the different resources used. Then follows conducting an LCA for recycling and reusing in order to determine the environmental performance and furthermore to compare the two scenarios. Lastly, the chapter includes sensitivity analysis to test the results and uncover what affects the results.

6.1 Crystalline silicon panel

In order to investigate recycling and reuse of c-Si PV panels, it is relevant to understand the compositing and different material fractions of the panels [Marsillac, 2021]. This section, therefore, describes the construction of c-Si panels.

As mentioned in the introduction, see section 1.1, c-Si panels account for the biggest share of PV panels installed on the marked. PV panels are constructed with several different layers and with an average size of 1,56m x 1,56m [Letcher and Fthenakis, 2018; European Commission, 2020]. Figure 6.1 illustrates the structure of and the different materials in a standard c-Si PV panel. The amounts of these materials are listed in table 6.1.

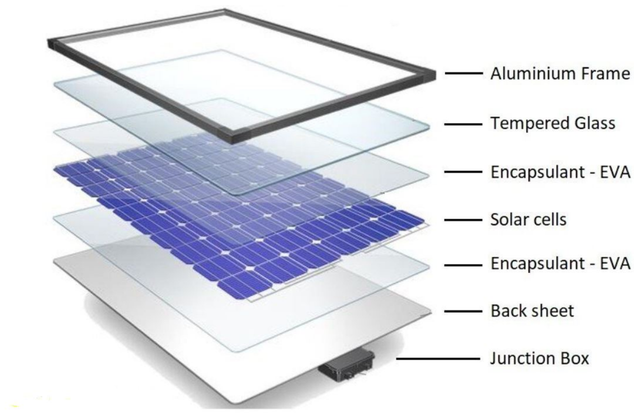


Figure 6.1. Composition of a c-Si PV panel [Svarc, 2020]

Part of panel	Materials	Percentage %
Surface glass	Glass	75,6
Encapsulant	Ethylene–vinyl acetate (EVA)	7,5
Solar Cell	Silicon (Si)	10,2
	Aluminium (Al)	0,4
	Copper (Cu)	0,9
	Silver (Ag)	0,1
Back Sheet and junction box	Polyethylene terephthalate (PET)	5,2
Frame	Aluminium (Al)	18,2

Table 6.1. Amount of materials used in the different parts of a c-Si panel based on European Commission [2020]. The total percentage is 118,2% as the aluminium frame is not included in the additional material composition [European Commission, 2020]

The exact composition of the materials varies depending on the manufacturer. However, it is common for PV panels that glass accounts for the majority of the PV panels [Duflou et al., 2018; Ilias et al., 2018].

The Solar cell for C-Si panels compose of crystalline silicon (c-Si), Silver (Ag), Aluminium (Al), and Copper (Cu) [Duflou et al., 2018]. C-Si has since 1970 been the most essential component for solar cells. C-Si is one of the most common materials that occur in the world. The solar cells are typically in the forms of single crystals monocrystalline silicon or polycrystalline silicon [Letcher and Fthenakis, 2018]. One difference between the two types is how the silicon is prepared. For the monocrystalline panels, the silicon is melted into a cylindrical shape where wafers are then cut from [EnergySage, 2021]. This ensures a constant structure of silicon crystals throughout the material. For the polycrystalline, the silicon is melted and put into a rectangular form. The silicon then cools off which enables different kinds of crystals to be formed. Therefore, these crystals have different shapes, sizes, and directions as oppose to the monocrystalline [Letcher and Fthenakis, 2018; EnergySage, 2021]. Additionally, the monocrystalline panels are more efficient but are more expensive compared to the polycrystalline [EnergySage, 2021].

Encapsulant is used to laminate the cells on both sides as a layer between the solar cell and the glass and back sheet. The thermoplastic, ethylene-vinyl–acetate (EVA) is the most commonly used for lamination of solar cells on the market as it is used in more than 90% of the productions [Letcher and Fthenakis, 2018].

The surface glass is usually 2-3 mm thick and transparent. This is used to protect the solar cells while still enabling sunlight to come through. This normally has a coating of anti-reflective film [Letcher and Fthenakis, 2018]. **Back Sheet** is the back of the panel and can either be made of glass or plastic and helps to weatherproof the panels [Ilias et al., 2018; Letcher and Fthenakis, 2018].

Junction box gathers the contact cables from the solar cells and is the electrical connection [Ilias et al., 2018]. **The frame** is mounted around the PV panel which seals the different layers in the panel [Letcher and Fthenakis, 2018].

6.2 Goal and Scope

This section includes a presentation of the goal and scope of the conducted LCA from this investigation.

The goal of the conducted LCA is to determine the environmental performance of the two EoL scenarios.

- The first scenario is recycling c-Si panels after 30 years of use with a degradation rate of 0,6% annually. This scenario takes departure in the recovery and recycling targets established in the WEEE Directive.
- The second scenario is reusing c-Si panels after 30 years of use with a degradation rate of 0,6% annually for additionally 15 years. This, therefore, require repairing, testing, and cleaning.

For further elaboration on the scenarios see section 3.3.1.

In extension hereof, the aim is to evaluate and compare the different scenarios. The LCA is based on a technology choice focusing on a c-Si PV panel. This technology is chosen since it is the most used and will continue to be the dominant technology in the coming decades, as described in section 1.1. The technology choice was necessary since the different technologies compose of different material compositions and recycling opportunities. Additionally, the goal is to contribute with knowledge regarding the environmental impacts of different EoL scenarios since most research in this field has focused solely on the recycling of PV panels. The intended audience for this study is therefore the PV industry, more specifically actors that affect the EoL. The results can serve to assist in decisions on how to improve PV panels' environmental performance at the EoL stage.

The studied product system in terms of recycling and reusing is illustrated in figure 6.2 and 6.3. These are presented on the following pages. The studied product system is defined based on figure 3.2 from the LCA methodology.

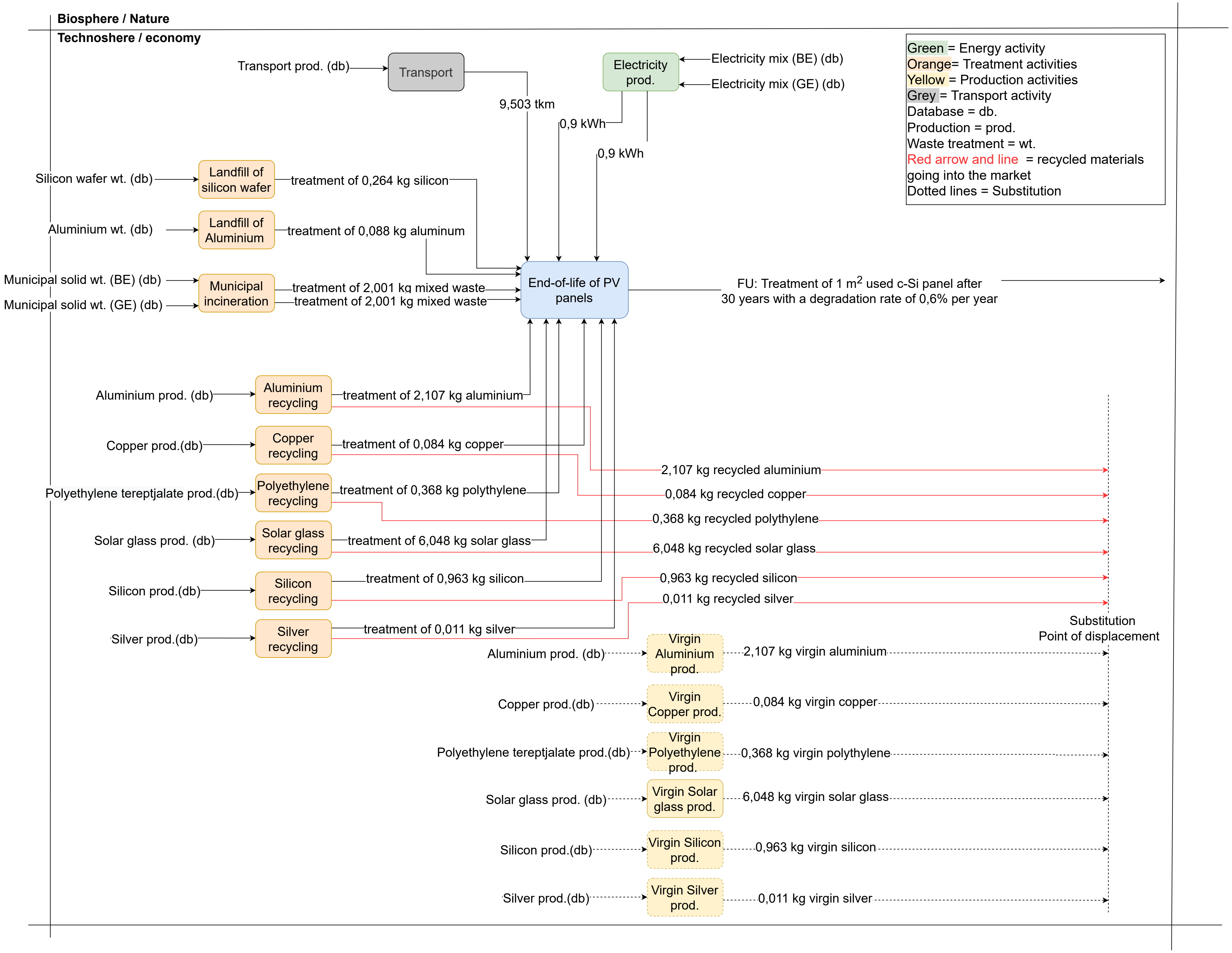


Figure 6.2. Product system for recycling scenario

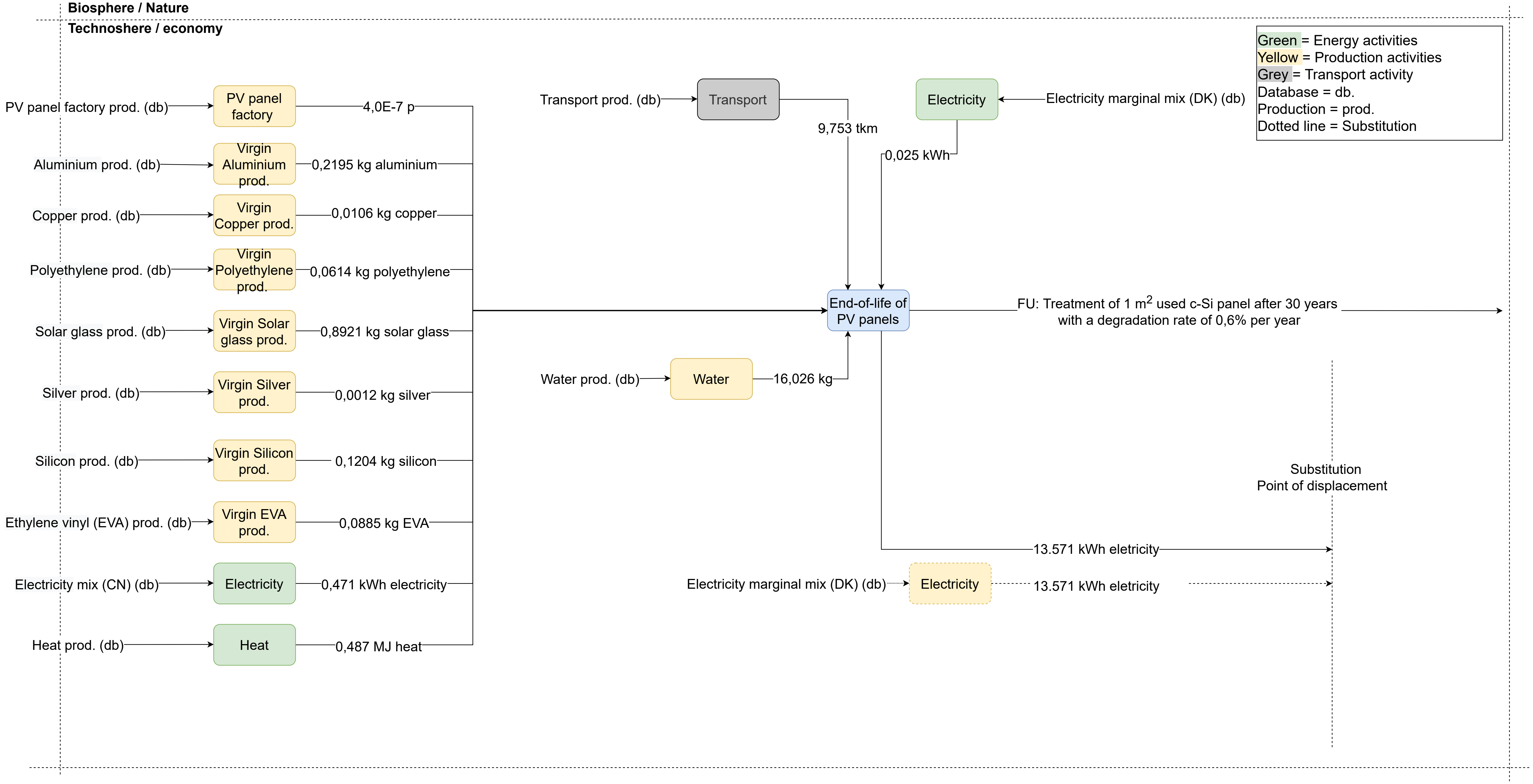


Figure 6.3. Product system for reuse scenario

The studied product system is only modeling the differences between the two investigated scenarios, which means that the focus is on the EoL stages (C2-C4) and the benefits/loads beyond the system boundary (D). The reasoning for not including the additional stages such as primary production, use of the panels in the first 30 years, etc. in the system boundaries is due to the assumption that these processes will be the same in the two scenarios and thereby can be omitted from the LCA.

6.2.1 Function, functional unit, and reference flow

Besides defining the product system and the system boundaries, it is also important to define a functional unit of the study since it is the reference point for the LCA and its results. Table 6.2 defines the function of the product, the functional unit, and the reference flow that has been used in the conducted LCA.

	Definition
Function	Treatment of 1 m^2 c-Si PV panels
Functional unit (FU)	Treatment of 1 m^2 used c-Si PV panel after 30 years with a degradation rate of 0,6% per year
Reference flow (RF)	Recycling: Recycling of 1 m^2 used c-Si PV panel after 30 years with a degradation rate of 0,6% per year Reuse: Reuse of 1 m^2 used c-Si PV panel after 30 years with a degradation rate of 0,6% per year

Table 6.2. Overview of the function, functional unit and reference flow

As described in section 1.4 multiple FU has been used in the previously conducted LCA studies within this field. However, $1m^2$ is chosen since it can be used for quantifying the environmental impacts at EoL efforts of PV systems [Frischknecht et al., 2020]. A limitation with the use of $1m^2$ as FU is, that it cannot be used to compare other technologies to PV nor for comparisons among PV technologies because of e.g. differences in modules, efficiencies and performance ratios [Frischknecht et al., 2020].

Because this study is not based on a case study of a specific PV panel or company, the c-Si panel is used as an example for the LCA. However, assumptions have been made about the panel in order to conduct the LCA. First of all the PV panel analysed does not include the inverter and cabling. This choice is based on the guidelines in PEFCR [European Commission, 2020]. It can be assessed that the inverters have a shorter lifespan of 15 years why these are not included [Urbina, 2022]. It is however assumed that the junction box is included in the analysed PV panel. This study works with an average PV panel with the size of 1,56m x 1,56m, an average weight of 11,8 kg/m^2 unframed, and 13,95 kg/m2 framed. These assumptions are based on information from PEFCR as well as the assumed lifespan of 30 years for PV panels. The degradation rate has been assumed to be 0,6% annually as this is the average between 0,5% and 0,7% which is suggested for c-Si panels in PEFCR [European Commission, 2020]. Further, in the reuse scenario, an extended lifespan of 15 years is assumed based on statements from Lunardi et al. [2018a].

The life cycle stages C and D are based on assumptions derived from literature research and interviews which have been necessary to fulfill the LCA. The LCA is conducted in SimaPro with the use of the method EF 3.0 (Environmental footprint). This method is designed to support the use of PEFCR and included the impact categories that are listed as relevant in the PEFCR to calculate the PEF profile [European Commission, 2020]. Furthermore, the LCIA will include the mandatory elements described in ISO 14040 and ISO 14044; classification and characterisation. Furthermore, the voluntary approach weighting is included to investigate the significance of the environmental impact.

6.3 Life Cycle Inventory Analysis

In this section, the Life Cycle Inventory Analysis (LCI) is presented for respectively the recycling and reuse scenarios. The data used for the LCA is collected and quantified into relevant in- and outputs for the defined product system. The data collected through interviews and literature is used as foreground data which is further connected to background data from Ecoinvent. Additionally, when information for the different processes has been lacking for structuring the LCA, assumptions have been made. These assumptions are further described in this section.

6.3.1 Recycling scenario

Table 6.3 includes the LCI for recycling of 1 m^2 used c-Si PV panel after 30 years with a degradation rate of 0,6% per year.

	Activity	Amount	Unit	Background data
Recycling	Frame and solar cell*	-2,107	kg	Aluminium alloy, AlMg3 GLO| market for | Conseq, U
	Cabling and solar cell*	-0,084	kg	Copper GLO| market for | Conseq, U
	Junction box and back sheet*	-0,368	kg	Polyethylene terephthalate, granulate, amorphous GLO| market for | Conseq,
	Surface glass*	-6,048	kg	Solar glass, low-iron GLO| market for | Conseq, U
	Solar Cell*	-0,011	kg	Silver GLO| market for | Conseq, U
	Solar Cell*	-0,963	kg	Silicon, solar grade GLO| market for | Conseq, U
Incineration	Polyethylene, glass, and EVA	2,001	kg	Municipal solid waste DE| treatment of, incineration | Conseq, U
	Polyethylene, glass, and EVA	2,001	kg	Municipal solid waste BE| treatment of, incineration | Conseq, U
Landfill	Aluminium	0,088	kg	Waste aluminium RoW| treatment of, sanitary landfill | Conseq, U
	Silver, Copper, and Silicon	0,264	kg	Waste, from silicon wafer production, inorganic RoW| treatment of, residual material landfill | Conseq, U
Electricity	Eletricity	0,90	kWh	Electricity, medium voltage DE| market for | Conseq, U
	Eletricity	0,90	kWh	Electricity, medium voltage BE| market for | Conseq, U
Transport	Transport	9,503	tkm	Transport, freight, lorry >32 metric ton, EURO4 RER| transport, freight, lorry >32 metric ton, EURO4 | Conseq, U

Table 6.3. Inventory table of recycling scenario. "*" indicates the resources that substitutes virgin resources on the market by being recycled. "-" indicates the substitution which avoids the production of virgin materials

Assumptions

The section includes a description of the chosen assumptions for the recycling scenario that have been made to carry out the LCA. This section aims to clarify the choices that have been made to account for missing or insufficient data which can cause uncertainties. The PEFCR by European Commission [2020] is used as a starting point for several of the assumptions since it has a well-argued material composition for the PV panels, this field is not well investigated, which entails few studies in this field. Further, this field is also new to the industry, which means that it is difficult to get data. Additionally, PEF acknowledges the standards ISO 14040 and ISO 14044 in which allocation should be avoided and substitution prioritised. Therefore, it can be argued that PEF can be used as a guideline in conducting a consequential LCA which is the case for this study.

Transport
Regarding transport for the current recycling scenario, there is uncertainty about where the PV panels are waste treated since multiple recycling facilities can be used. Denmark has no end-processing facilities and only a few pre-processing facilities for WEEE waste [Zacho et al., 2018]. Knowledge gained from the conducted interviews stressed three waste facility locations. Therefore, an average distance has been used for the transport from Denmark to a waste facility. The PV panel waste is produced and collected from all the municipal recycling sites as well as from the PV farms which means that the transportation could potentially differ from panel to panel. This could affect the environmental impacts.

	Distance (km)
Denmark –>Reiling (Germany)	620
Denmark –>Exner Trenntechnik (Germany)	571
Denmark –>Maltha (Belgium)	853
Average distance	**681**

Table 6.4. Transport distances from Denmark to recycling facilities in Germany and Belgium

Further, the transportation of the PV panels is assumed to be managed in a *lorry >32 metric tons EURO4* as this type is used as default in PEFCR for PV panels [European Commission, 2020].

Waste treatment
The assumptions made for the waste treatment are related to different recycling percentages for the materials used in a PV panel. The PEFCR for PV panels underlines that a PEF study shall include a statement about the recyclability of the materials. Therefore, table 6.5 below states the used recycling percentages used in this LCA investigation. Further, the recycling assumptions are based on different sources which are highlighted in the table. When recyclability values are not available these shall be set equal to 0 according to PEFCR.

	Percentage (%)	Source
Aluminium	96	[Li et al., 2018]
Polyethylene terephthalate (PET)	60	[Li et al., 2018]
Glass	67,8	[Li et al., 2018]
Silicon (Si)	8	[Urbina, 2022]
Cobber (CU)	79	[Urbina, 2022]
Silver (Ag)	90	[Urbina, 2022]
Ethylene-vinyl acetate (EVA)	0	

Table 6.5. Recycling rates for the materials used in a PV panel

Further, it has been assumed that the materials that are not recycled from the materials; PET, glass, and EVA are sent to municipal incineration since the quality is low and therefore not suited for recycling. Additionally, the metals and silicon that are not recycled are assumed to be disposed through landfilling based on statements from Daljit Singh et al. [2021]. For the municipal incineration it is assumed that it is waste treated in either Germany or Belgium since the recycling facilities are located in these countries [Lempkowicz, 2022; Forti, 2022; Stenstrøm, 2022]. Therefore, the waste amounts are equally distributed in the background data for these two countries, see table 6.3.

Furthermore, electricity is needed for the recycling plants which has been included [Urbina, 2022]. Urbina [2022] presents that recycling plants with mechanical processes on average use 50-100 kWh per tonnes and for recycling plants with metal processing the average is 494 kWh per tonnes. The mechanical processes are calculated based on the total amount of recycled materials which is 9,581 kg. This is due to the assumption that all of the recycled material need mechanical processing. Additionally, the metal processing is calculated for the metals including; aluminium, copper, and silver. An average of the two processes have been calculated and added with respectively the German and the Belgium electricity mix from the background data. This is also based on the assumption that the Danish PV panels are shipped to either Belgium or Germany for recycling [Forti, 2022; Lempkowicz, 2022; Frahm, 2022].

6.3.2 Reuse scenario

This section presents the LCI for the reuse scenario and the assumptions made. Table 6.6 includes the LCI for the reuse scenario.

	Activity	Amount	Unit	Background data
Repair and refurbishment	Frame and solar cell	0,2195	kg	Aluminium alloy, AlMg3 GLO| market for | Conseq, U
	Cabling and solar cell	0,0106	kg	Copper GLO| market for | Conseq, U
	Junction box and back sheet	0,0614	kg	Polyethylene terephthalate, granulate, amorphous GLO| market for | Conseq,
	Surface glass	0,8921	kg	Solar glass, low-iron GLO| market for | Conseq, U
	Solar Cell	0,0012	kg	Silver GLO| market for | Conseq, U
	EVA	0,0885	kg	Ethylene vinyl acetate copolymer RoW| market for ethylene vinyl acetate copolymer | Conseq, U
	Solar Cell	0,1204	kg	Silicon, solar grade GLO| market for | Conseq, U
Energy	Electricity	0,47107	kWh	Electricity, medium voltage CN| market group for | Conseq, U
	Heat	0,486639	MJ	Heat, district or industrial, natural gas RER| market group for | Conseq, U
	PV panel factory	4,0E-7	p	Photovoltaic panel factory GLO| market for | Conseq, U
Transport	Transport	9,753	tkm	Transport, freight, lorry >32 metric ton, EURO4 RER| transport, freight, lorry >32 metric ton, EURO4 | Conseq, U
Testing and cleaning	Testing	0,025	kWh	Energy mix (marginal supplier 2010-2020)
	Cleaning	16,026	kg	Tap water Europe without Switzerland| market for | Conseq, U
Produced Electricity*	Electricity	-13.571	kWh	Energy mix (marginal supplier 2010-2020)

Table 6.6. Inventory table of reuse scenario. "*" indicates the produced electricity in the 15 years which substitutes energy on the market. "-" indicates the substitution which avoids the production of virgin materials

Assumptions

This sections elaborate on the data used in table 6.6 and appertaining assumptions for the reuse scenario.

Transport

The transportation distance in this scenario is based on two reuse scenarios. The first scenario is based on Danish used PV panels being transported to the German company Supportive where the panels are prepared for reuse. The second reuse scenario focuses on reused PV panels from a German solar farm which are transported to Ennogie with a cleaning and testing stop at the company Indiko in Denmark. This assumption is based on Ennogie's experience with their reused panels. Therefore, the transportation distance used for the reuse scenario is based on an average between the two scenarios: 699,25 km. Further, a lorry >32 metric tons EURO4 is also used for the reuse scenario.

Repair and refurbishment in the reuse scenario

As the reuse market is not developed and widely implemented in Denmark yet no data is available regarding how much repairment and refurbishment are needed for the reused PV panels in the extended lifespan of 15 years. However, it is assumed that repairment or refurbishment is needed. In many cases, the failure is related to problems with cabling or the junction box, but the failures can also be more complex like sealing, framing, or reparation of damaged cells [Urbina, 2022]. This highlights that failures can occur in the whole PV panel, which entails the assumption that 10% of the PV panel will need a repairment or refurbishment during the extended 15 years. As the repair and refurbishment can occur in several parts of the PV panels, it is assumed that the 10% added resources for repair and refurbishment are the same resources needed to produce a new PV panel. Therefore, the modeling of the repair and refurbishment is done by adding 10% of a new panel to the reuse scenario to illustrate the resources needed for these processes. The background data for the production of a new PV panel is assumed to be from China, as China is the main manufacturer of PV panels Stenstrøm [2022]; Lempkowicz [2022]. Furthermore, the electricity, heat, and PV panel facility needed to produce PV panels are based on an existing database for PV panels in EcoInvent. The existing PV panel data in the background data is not used due to uncertainties in several of the inputs. The modeling of the inputs for c-Si PV panels is instead based on the material composition listed in table 6.1.

Prepare for reuse

In order to reuse the panels, they need to be tested and cleaned [Hornbeak, 2022]. The assumption regarding the electricity used for testing is based on Ennogies procedure as they use a flash test method which is based on estimations from Hornbeak [2022]. Ennogie could not provide the exact data on the water used for cleaning, therefore the water use is based on Solar Post [2018]. Here, it is estimated that 2,5 m^3 per panel is needed. This is divided out on the m^2 panel which is why 0,016 m^3 is assumed needed for cleaning of the panels.

Energy marginal mix

In the reuse scenario, it is assumed that the energy produced in the additional 15 years is substituting energy on the market. As the LCA is conducted as a consequential LCA, the energy substituted on the market is from the marginal suppliers. Therefore, the energy sources that have increased their production over the past 10 years are included as these will be the "actual" affected [Matthews et al., 2015].

Source of electricity	**Generation in 2010 (GWh)**	**Generation in 2019 (GWh)**	**Changes in energy mix 2010-2019 (GWh)**	**Classification**	**Applied electricity mix 2020 (%)**
Coal	17.006	3.062	-13.944	Old	0
Oil	774,00	263	-511	Old	0
Natural gas	7.906	1.184	-6.722	Old	0
Biofuels	3.680	4.973	1.293	Current	11,74
Waste	1.660	1.718	58	By-product	0
Hydro	21,00	16	-5	Old	0
Solar PV	6	1181	1175	Current	10,67
Wind	7.809	16353	8.544	Current	77,59 (25,44% offshore and 52,14% onshore)
Total	**38.862**	**28.751**	**-10.112**		**100**

Table 6.7. Electricity sources. Data from International Energy Agency [2022]. The approach to identifying the marginal suppliers and setting up the table is inspired by Muñoz [2020]. Green shows the three energy sources in prospering. Red illustrates the energy sources that have declined. Regarding the wind, it is assumed that the distribution between onshore and offshore are the equal to the current capacity distribution according to Energistyrelsen [2022]

Table 6.7 shows that the three energy sources in prospering are; Biofuels, Solar PV, and Wind. Furthermore, waste is also prospering. However, this cannot be used in marginal supplier mix as it is considered a by-product. Thereby, an increase in demand for electricity will not increase the waste produced for incineration [Muñoz, 2020].

Table 6.8 shows the inventory for the energy marginal mix which is used to model the substitution of energy in the reuse scenario and applied as the used electricity for testing the panels. The total energy produced by the PV panels with a degradation rate of 0,6& in the extra 15 years is 13.571 kWh. This energy is thereby substituting energy on the market and avoiding the production hereof. The assumption of the annual produced electricity is based on the PEFCR in which it is stated that the average production in the optimal angle is 1130 kWh/m^2 in a Danish context [European Commission, 2020]. The first year the PV panel produces electricity it is therefore assumed that it produces 1130 kWh/m^2. Subsequently, the efficiency will degrade by 0,6% annually. In year^{30} the PV panel will produce 949 kWh/m^2. The calculation of the additional 15 years does therefore take departure in the 949 kWh/m^2 and a degradation rate of 0,6% for the 15 years which is summarised and results in a total of 13.571 kWh.

	Activity	Amount	Unit	Background data
Electricity	Offshore wind	3.452,6124	kWh	Electricity, high voltage DK| electricity production, wind, 1-3MW turbine, offshore | Conseq, U
	Onshore wind	7075,8021	kWh	Electricity, high voltage DK| electricity production, wind, 1-3MW turbine, onshore | Conseq, U
	Solar PV	1.448,0499	kWh	Electricity, low voltage DK| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Conseq, U
	Biofuels	1.593,4710	kWh	Electricity, high voltage CH| electricity, high voltage, biofuels, import from Germany | Conseq, U

Table 6.8. Inventory table for marginal energy mix for reuse scenario

The aim has been to use background data from Denmark. However, there was only background data for *Biofuels* from Switzerland which is why this one has been included in the marginal mix.

6.4 Life Cycle Impact Assessment

The following section presents the LCIA results of the two analysed EoL scenarios. The results are used to answer the second sub-question.

6.4.1 Comparison - Recycling vs. Reuse

The LCIA aims to evaluate the significance of the potential environmental impacts. This has been done by associating inventory data with environmental impact categories from the method EF 3.0. However, some of the impact categories have been deselected to follow the guidelines in PEFCR and the impacts categories designated in this.

Table 6.9 presents the characterised results of 1m^2 used c-Si PV panel for the two investigated EoL scenarios; recycling and reuse. The negative values presented in the table indicate avoided impacts or environmental improvements while the positive values indicate the amount of each impact.

Environmental impact categories	Unit	Recycling	Reuse
Climate change	kg CO2 eq	-7,1608	-638,0055
Ozone depletion	kg CFC11 eq	0,0000	-0,0001
Ionising radiation	kBq U-235 eq	-0,0699	-8,1229
Photochemical ozone formation	kg NMVOC eq	-0,0260	-1,8963
Particulate matter	disease inc.	0,0000	0,0000
Human toxicity, non-cancer	CTUh	0,0000	0,0000
Human toxicity, cancer	CTUh	0,0000	0,0000
Acidification	mol H+ eq	-0,04312	-0,9948
Eutrophication, freshwater	kg P eq	-0,0032	-0,2737
Eutrophication, marine	kg N eq	-0,0079	-0,5370
Eutrophication, terrestrial	mol N eq	-0,09109	-5,7911
Ecotoxicity, freshwater	CTUe	-374,6162	-21422,0187
Land use	Pt	-16,8792	-8850,5761
Water use	m3 depriv.	-1,0618	-191,2905
Resource use, fossils	MJ	-81,6576	-8582,6435
Resource use, minerals and metals	kg Sb eq	-0,0012	-0,0249

Table 6.9. Characterisation results for recycling and reuse of 1m^2 used c-Si PV panel after 30 years with a degradation rate of 0,6% per year. Method: EF 3.0

As presented in table 6.9 both EoL scenarios have a positive impact on the vast majority of the impact categories. However, it is also evident that the reuse scenario is significantly better than the recycling scenario in all the investigated impact categories.

6.4.2 Environmental impact of reuse

As aforementioned, reusing 1m^2 of c-Si panel performs better than recycling. It is therefore deemed relevant to investigate the contribution of the different activities which are shown in table 6.10.

Environmental impact categories	Unit	Transport	Repair / refurbishment	Prepare for reuse	Electricity	Total
Climate change	kg CO2 eq	0,8940	14,0443	0,0097	-652,9535	-638,0055
Ozone depletion	kg CFC11 eq	0,0000	0,0000	0,0000	-0,0001	-0,0001
Ionising radiation	kBq U-235 eq	0,0585	0,2704	0,0008	-8,4526	-8,1229
Photochemical ozone formation	kg NMVOC eq	0,0050	0,0519	0,0000	-1,9532	-1,8963
Particulate matter	disease inc.	0,0000	0,0000	0,0000	0,0000	0,0000
Human toxicity, non-cancer	CTUh	0,0000	0,0000	0,0000	0,0000	0,0000
Human toxicity, cancer	CTUh	0,0000	0,0000	0,0000	0,0000	0,0000
Acidification	mol H+ eq	0,0043	0,0794	0,0000	-1,0786	-0,9948
Eutrophication, freshwater	kg P eq	0,0001	0,0054	0,0000	-0,2792	-0,2737
Eutrophication, marine	kg N eq	0,0015	0,0157	0,0000	-0,5542	-0,5370
Eutrophication, terrestrial	mol N eq	0,0167	0,1817	0,0001	-5,9896	-5,7911
Ecotoxicity, freshwater	CTUe	11,2184	629,5790	0,1803	-22062,9963	-21422,0187
Land use	Pt	16,3034	55,1547	0,0663	-8922,1006	-8850,5761
Water use	m3 depriv.	0,0461	2,1247	0,6917	-194,1530	-191,2905
Resource use, fossils	MJ	13,7955	170,4307	0,1339	-8767,0037	-8582,6435
Resource use, minerals and metals	kg Sb eq	0,0000	0,0020	0,0000	-0,0268	-0,0249

Table 6.10. Characterisation results of reusing 1m^2 c-Si PV panel after 30 years with a degradation rate of 0,6% per year. Method: EF 3.0

From the table, it can be derived that energy causes the savings as this substitutes produced energy on market. Furthermore, repair/refurbishment is the activity that causes the highest environmental impact in the reuse scenario. Figure 6.4 shows the percentage distribution of how much each activity within reuse contributes to the environmental impacts. The negative values illustrate the impacts that are being avoided.

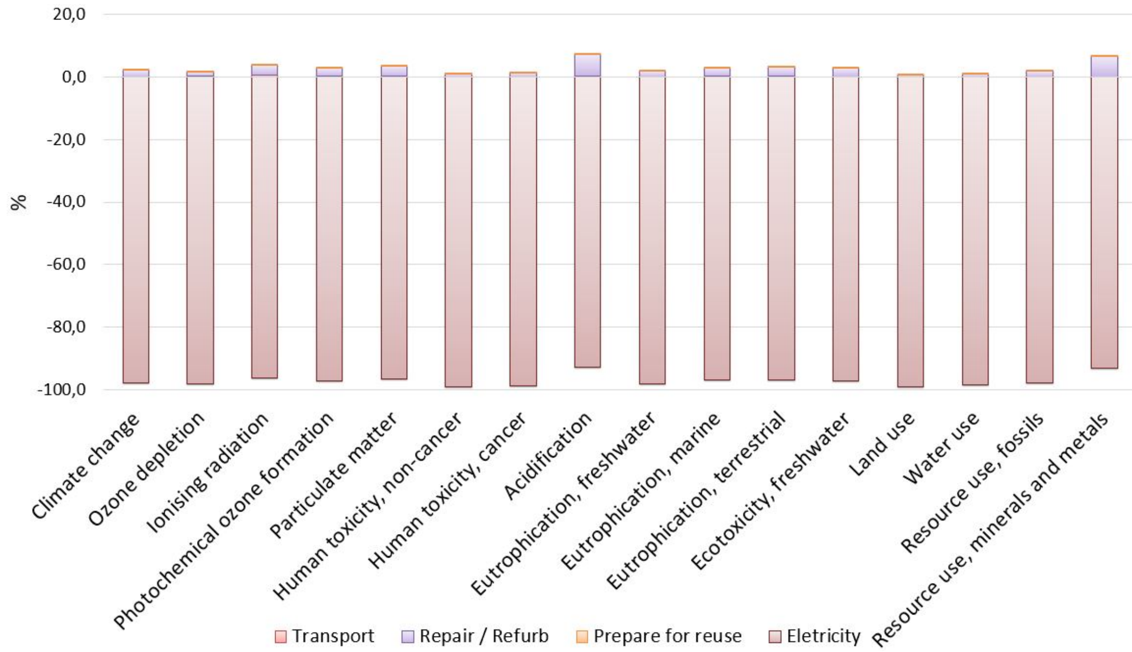


Figure 6.4. Percentage distribution of the environmental impact from each activity

The reuse scenario does overall avoid environmental impacts within every environmental impact category. This is caused by the substitution of energy. Figure 6.4 illustrates that repair / refurbishment is the main contributor to the negative impacts. This is caused by the new materials which are added in order to repair the PV panels. *Addification* and *Resource use, minerals, and metals* have the highest percentage distribution of negative environmental impacts. Furthermore, it can be deduced that the substitution of energy (marginal suppliers) contributes to avoiding environmental impacts within each category.

Weighting

It is furthermore deemed relevant to investigate the significance of the different environmental impacts compared to each other. Weighting allows for a comparison of the significance of the impact categories. By using weighting the environmental impact categories are multiplied with a weighting factor. The EF 3.0 uses a panel-based weighting method [Centre et al., 2018]. This means that a panel of stakeholders has been included to establish the weighting factors. However, this does concern uncertainties due to the selection of stakeholders and their personal experiences and bias [Pizzol et al., 2017]. Table 6.5 shows the weighting results of the reuse scenario.

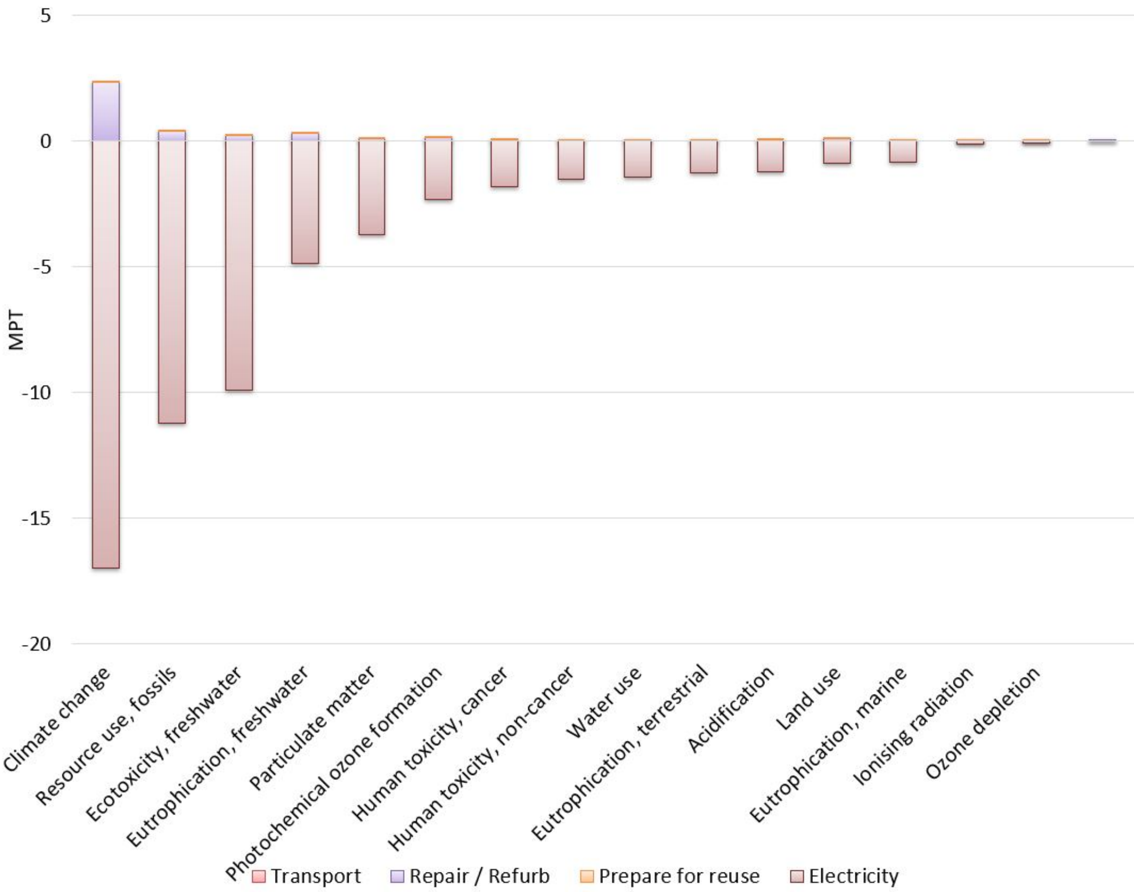


Figure 6.5. Weighting of the reuse scenario including the different activities with the factor of mPt. Method: EF 3.0

From the weighting, it can be derived that Repair/refurbishment causes the most significant environmental impacts in terms of *Climate Change* and *Resource use, fossils*. As opposed, the weighting does also show that the substitution of energy entails the most significant environmental impacts savings in these categories.

6.5 Sensitivity Analysis

This section includes a sensitivity analysis for both the recycling and reuse scenario, which is a useful analysis to investigate the effect of changing certain parameters in the LCA and how this affects the results [Matthews et al., 2015]. The performed sensitivity analysis will initially examine how the choice of method affects the results. Moreover, an analysis of the chosen data was deemed relevant to explore how different variations of the chosen data will affect the results for treatment of $1m^2$ used PV panel at the EoL stage for both scenarios. Additionally, the efficiency of the panels is investigated to determine how this affects the lifespan of the panels.

6.5.1 Method choice

This section shows how a method choice of ReCiPe2016 affects the results. The method EF 3.0 is currently used to analyse the results. However, multiple of the LCA studies identified in the SOTA in section 1.4 use the method ReCiPe2016 to assess the LCA results. Therefore, is this method applied and compared with the results from the EF 3.0 method, but only for the midpoint categories; *Climate change* and *Global warming* in respectively EF 3.0 and ReCiPe2016. The comparison of the result is presented in table 6.11

	Recycling	**Reuse**
EF 3.0	-7,116 kg CO_2-eq	-643,548 kg CO_2-eq
ReCiPe2016	-7,059 kg CO_2-eq	-638,987 kg CO_2-eq
Difference	0,057 kg CO_2-eq	4,561 kg CO_2-eq

Table 6.11. Comparison of the methods EF 3.0 and ReCiPe2016 on the midpoint categories Climate change and Global warming from the respectively methods

As determined in table 6.11, the results for the chosen midpoint categories are quite similar but not directly comparable. This is something to be aware of if this study should be compared with other studies.

6.5.2 Data inputs

In this section, the effect of the data input for the conducted LCA is investigated to determine how sensitive the results are to variations in the data input.

Recycling scenario

For the recycling scenario, a ± 10% variation has been chosen to test the sensitivity of the data inputs. The negative variation has been used to investigate how a decreased recycling rate for the materials will affect the results. A maximum and minimum of the intervals could have been used for the transportation since an average between different assumptions has been used in this regard. However, to streamline the analysis the ± 10% variation has been used for all the data inputs. In table 6.12 the results of the sensitivity analysis for the recycling scenario are illustrated.

Input	Used data	Variation	Change in results
Transportation	Lorry transport 9,503 tkm	10,45 tkm (+10%)	-1,26 %
Waste treatment	Incineration (DE) 2,001 kg	2,2 kg (+10%)	0%
	Incineration (BE) 2,001 kg	2,2 kg (+10%)	0%
	Waste aluminium 0,088 kg	0,968 kg (+10%)	0%
	Waste Silicon 0,264 kg	0,29 kg (+10%)	0%
Recycling rates	Aluminium 2,107 kg	1,9 kg (-10%)	-4,35%
	Copper 0,084 kg	0,076 kg (-10%)	0%
	PET 0,368 kg	0,331 kg (-10%)	-0,14%
	Glass 6,048 kg	5,44 (-10%)	-0,702%
	Silicon 0,963	0,867 (-10%)	-5,62%
	Silver 0,011 kg	0,0099 (-10%)	0%

Table 6.12. Sensitivity analysis for recycling scenario of 1 m^2 used c-Si PV panel. Midpoint category: Climate change. Method: EF 3.0

The results in table 6.12 show that most of the variations in the data used for the recycling scenario do not have a significant influence when changing the input with ± 10%. This entails that the assumptions applied in the conducted LCA do not affect the results considerably. However, the changes in the recycling rates for aluminium and silicon have the biggest effects on the results with a change of respectively -4,4% and a -5,6% change for the total CO_2-eq.

Reuse scenario

The data used for the different inputs in the reuse scenario will be tested with a chosen variation of +10% to investigate the sensitivity of these data inputs. Minimum and maximum variations have been deselected in this investigation. In table 6.13 the results of the sensitivity analysis for the reuse scenario are illustrated.

Input	Used data	Variation	Change in results
Transportation	Lorry transport 9,753 tkm	10,7 tkm (+10%)	-0,16 %
Prepare for reuse	Energy 0,025 kWh	0,075 kWh (+10%)	0%
	Waster usage 16,03 kg	17,60 kg (10%)	0%
Repair/refurbish	Production of new components 0,1 m^2	0,11 m^2 (+10%)	-0,31%
Substitution	Energy 13685,7 kWh	15000 kWh (+10%)	10,09%

Table 6.13. Sensitivity analysis for recycling scenario of 1 m2 used c-Si PV panel. Midpoint category: Climate change. Method: EF 3.0

In table 6.13 it is seen that the influence of the energy substitution processes is considerable;

a +10% variation results in a 10,1% change for the total CO_2-eq for the EoL. An explanation for this result could be that the other related reuse processes have such a small impact compared with the substitution which is the main contributor to the result. Based on the sensitivity analysis in tables 6.12 it can be concluded that the recycling rate for aluminium and silicon has the most significant influence in the recycling scenario. For the reuse scenario, the substitution of energy has the most significant influence on the LCA results as shown in table 6.13.

6.5.3 Efficiency

Another aspect that is relevant to investigate in terms of PV panels is the degradation rate and how this affects the efficiency. The efficiency does normally correlate with the warranty of the PV panels [Dodd et al., 2019]. Generally, the warranty terms are that the efficiency of the panels needs to be 80% after 25 years of use from the first produced electricity [Dodd et al., 2019]. According to the PEFCR, a linear regression shall be used to determine the annual degradation in a long-term perspective [European Commission, 2020]. If the efficiency is 80% after 25 years of use, the annual degradation rate is 0,8 % per year. This sensitivity analysis will include different degradation rates in order to determine how this affects the efficiency and thereby the lifespan of the PV panels. Table 6.14 presents the chosen degradation rates.

Annual degradation rate (%)	**Source**
0,25 (low)	[Hornbeak, 2022]
0,6 (average)	[European Commission, 2020]
1 (high)	[European Commission, 2020]

Table 6.14. Degradation rate for c-Si panels

The presented degradation rate has been used to investigate when the PV panels will reach 80% efficiency which figure 6.6 illustrates.

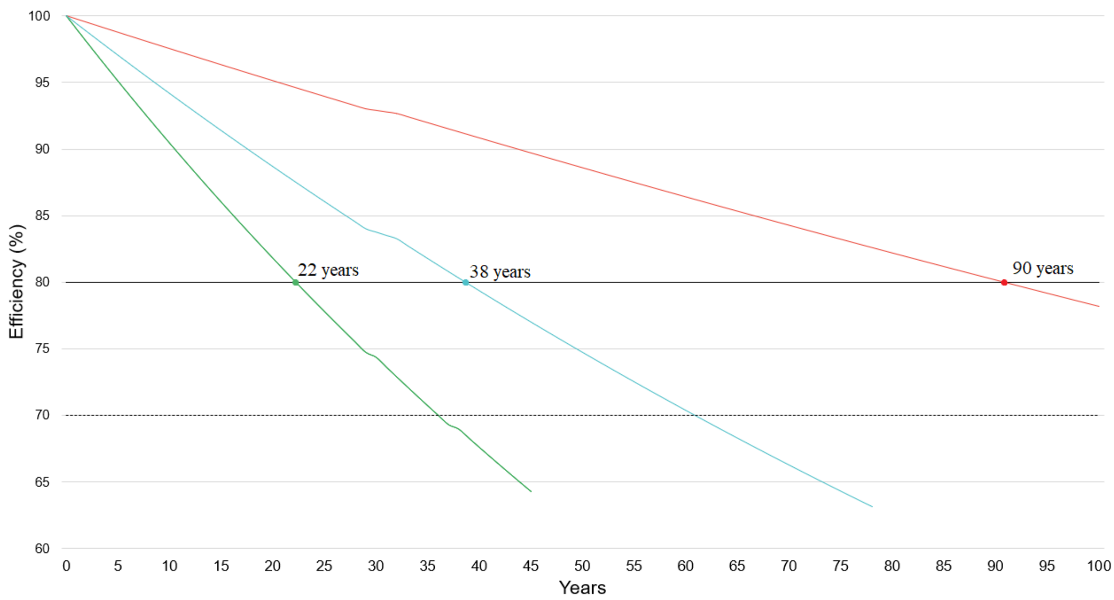


Figure 6.6. The annual degradation rate. The line shows the different annual degradation rates applied. Green = 1%, Blue = 0,6%, Red = 0,25%. The black line illustrates 80% efficiency whereas the black dotted line illustrates 70% efficiency

From figure 6.6 the lifespan of the three degradation rates causes respectively a lifespan of 22 (1%), 38 (0,6 %) and 90 (0,25%) years. This shows that the lifespan of the PV panel can be used for 38 years with an average degradation rate of 0,6% per year. This indicates that there properly are several additional years of use in PV panels before they reach an efficiency of 80% compared to the average lifespan of 25-30 years suggested in the literature, see section 1.4. A dotted line at a 70% efficiency has also been included as an example to represent the lifespan if a 70% efficiency is accepted. However, the linear regression cannot be transferred directly to the real context as there are several parameters affecting this. Stenstrøm [2022] gives an example hereof as he compares a panel in Denmark with a panel in Italy. Due to the weather and climate, the degradation in Denmark will not be as fast as in Italy [Stenstrøm, 2022]. However, the lifespan and degradation rate remain a field with limited research. Additionally, the method for calculating the lifespan and the durability of the panels have not yet been defined in any standards [Dodd et al., 2019].

An aspect that needs to be considered in relation to prolonging the lifespan of the panels is if the developers choose to replace them before the panels reach their EoL due to repowering [Pedersen, 2022]. This was the case with the panels that Ennogie bought from Germany where the panels were only 5-10 years Hornbeak [2022]. Therefore, there is a risk of developers switching out the panels prior to they reach 80% efficiency due to development in technology.

6.6 Interpretation

The environmental performance of recycling 1m^2 of used c-Si panel is -7,1608 kg CO_2-eq. Whereas, the environmental performance of reusing 1m^2 of used c-Si panel is -638,0055 kg CO_2-eq. The LCA results conducted from this study can be used as inputs for decision-making by the intended audience. The LCA results indicate that the modeled reuse scenario has a positive effect on the environment and is, therefore, better than the modeled recycling scenario. By weighting the results from the reuse scenario, it can be derived that the activity repair/refurbishment causes the largest impact in terms of the environmental impact categories; climate change and resource use, fossils. However, the substituted energy counteracts this as this activity causes greater savings within these impact categories. Based on the sensitivity analysis it can be concluded that the choice of the EF 3.0 method does not affect the LCA results significantly. However, the methods are not directly comparable. Furthermore, the sensitivity analysis regarding the data inputs shows the recycling rate for aluminium and silicon has the most significant influence in the recycling scenario. In the reuse scenario, the substitution of energy has the most significant influence on the LCA results. Additionally, the degradation rate also influences the lifespan of the PV panels if the efficiency should not be inferior to 80%.

Additionally, it is relevant to interpret the uncertainties regarding the data and modeling hereof. As this study does not engage in a specific case study, the foreground data used for the modeling have been provided through literature which is secondary data. The data used is therefore more generic and not specific as the foreground data is not provided from a primary source such as real-life treatment of the panels. However, this is accommodated by using the conducted interview to support the assumptions made. Furthermore, Ennogies procedure for testing and cleaning has been the foundation for the refurbishment of the panels in order to reduce uncertainties. However, Ennogie could not provide the exact data for water used for cleaning. Therefore, the water use is based on a source that includes data on the water for cleaning PV panels in India which creates uncertainty. The background data have been selected based on the geographical location of the specific activity. However, some of the background data were not available for the specific location e.g., biofuels and therefore the data on biofuels from Switzerland have been included. Furthermore, due to limitation in the EcoInvent database, it has been necessary to gather and model the different plastic types under the same recycling treatment.

7 Circular strategies for the photovoltaic industry

In this section, the third sub-question presented in section 2.1.1 is answered. This chapter takes departure in the results from the first analysis regarding the barriers identified by actors and the second analysis on LCA. The results from these analyses have been used to suggest circular strategies with appertaining recommendations. Based on the results from the second analysis regarding the LCA it can be concluded that reuse contributes to the largest savings in terms of environmental impacts compared to recycling. Therefore, the circular strategies are exclusively suggested within the slow strategy as this aims at furthering reuse, see section 4.2. Here, the circularity deck by [Konietzko et al., 2020b] serves as guidance for conducting the strategies. Furthermore, recommendations within the innovation principles product, business model, and ecosystem are suggested. According to Konietzko et al. [2020b], it is essential to include the three innovation principles to ensure a transition towards CE. Here, the barriers identified through interviews, see section 5.2.2, are the inspiration for the suggested circular strategies and recommendations. This is deemed relevant in order to minimise these barriers which enable further reuse of PV panels. Therefore, this chapter takes departure in the interviews with the following actors;

- Hornbeak [2022] from Ennogie (developer of reused and new roof-mounted panels)
- Stenstrøm [2022] from Better Energy (developer of new ground-mounted panels)
- Forti [2022] from Ragn-Sells (waste operator)
- Frahm [2022] from European Recycling Platform (collective scheme)
- Harboe-Jepsen [2022] from Elretur (collective scheme)
- Lempkowicz [2022] from PV Cycle (collective scheme)
- Kristensen [2022] from the Danish PV Association (Trade association)

7.1 Product

In this section, recommendations are suggested which takes departure in the product innovation principle. Here, the aim is to prolong the lifespan of the PV panels according to the slow strategy. This strategy strives to minimise the barriers; Lack of design that further reuse, and limited focus/knowledge on reuse of PV panels.

7.1.1 Additional requirements for the Ecodesign Directive

This section takes departure in two proposed addition to the current Ecodesign framework. This includes a *"Discussion paper on potential Ecodesign requirements and Energy Labelling scheme(s) for photovoltaic module, inverters and systems"* by European Commission [2021] and *"Proposal for new Ecodesign for Sustainable Products Regulation"* by European Commission [2022a]. The discussion paper exclusively focuses on PV modules whereas the proposal for new Ecodesign regulation has a broader focus on the general framework of the Ecodesign Directive.

As described in section 4.2, the strategies within the product innovation principles focus on the design of the product. The current Ecodesign Directive does not contain specific requirements for PV panels and does moreover focus on the use phase and the product's energy efficiency, see section 1.2.1. A switch in focus in terms of the Ecodesign has however recently occurred, as specific requirements for PV panels and new general requirements for the Ecodesign Directive which focus more on prolonging the lifespan have been suggested. In April 2021, European Commission [2021] published a discussion paper that suggests specific Ecodesign requirements for PV panels placed on the EU market. These suggested requirements broaden the focus of energy efficiency by adding requirements within design quality, durability, and repairability. Regarding the quality and durability, testing of the PV panels is suggested. Furthermore, the design qualification should minimum meet the EN IEC 61215 [1] series of standards [European Commission, 2021]. Here, the degradation rate is also mentioned as this affects the performance during the PV's lifespan. It is proposed that the manufacturer should state the expected degradation rate based on a specific procedure. This follows from the lack of standardised methods and explanation for how the power guarantee has been determined. Additionally, requirements for repairability are proposed which include that the manufacturer needs to provide information on the possibility to repair or replace the junction box and containing bypass diodes. However, these suggested requirements have not yet been applied to the Ecodesign Directive. The suggestions indicate that the focus of the Ecodesign Directive has started to broaden.

In March 2022, European Commission [2022a] published a *"Proposal for new Ecodesign for Sustainable Products Regulation"* which build on top of the existing Ecodesign Directive. The addition aims to improve circularity and environmental performance of products. The new framework will enable to set requirements regarding [European Commission, 2022a]:

- "product durability, reusability, upgradability and reparability"
- "presence of substances that inhibit circularity"
- "energy and resource efficiency"
- "recycled content"
- "remanufacturing and recycling"
- "carbon and environmental footprints"
- "information requirements, including a Digital Product Passport"

Requirements within the aforementioned categories incite further repairing of products and do thereby entail a prolonged lifespan. The Digital Product Passport ensures that specific information on resources used in the products is provided. This facilitates transparency and easier repairment and recycling of the products [European Commission, 2022a]. Thereby, this aligns with the *"Right to repair"* initiative, which aims to make repair easier for end-consumer while also advancing CE development. *"Right to repair* stems from issues arising from the current Ecodesign Directive such as it is difficult for the end-consumer to repair their product due to e.g. lack of spare parts, the product are constructed in such a way that

[1] "IEC 61215-1:2021 lays down requirements for the design qualification of terrestrial photovoltaic modules suitable for long-term operation in open-air climates." [European Committee for Electrotechnical Standardisation, 2021]

they cannot be separated and repaired, or lack of technical information (e.g. manuals). As a result, product repair is heavily reliant on expert repairers who have access to technical information and can obtain spare components. In this regard, the current Ecodesign Directive has been criticised by stakeholders as this fails to include the essence of *"Right to repair"* [European Parliament, 2022]. The proposal for the new Ecodesign Directive encompasses the Digital Product Passport which should provide information across the supply chain - from the manufacturer, and developer to consumers. The aim is to ensure the technical information is also available for the general public [European Commission, 2022a] which further the *"Right to repair* by end-consumers. The Digital Product Passport, therefore, contributes to the circular strategy *Design for ease of maintenance and repair (p)* by Konietzko et al. [2020b]. Furthermore, the increased product information aligns with the information strategy *"Build material database ecosystems (e)"* by Konietzko et al. [2020b] where information on the products is shared across the ecosystem. Therefore, the Digital Product Passport can support both the product and ecosystem principle for the slow and information strategies. Digital Product Passport contributes to better communication by transferring and sharing information on the PV panels amongst the ecosystem [European Commission, 2022a] which is deemed essential in the transition towards CE. The suggested Digital Product Passport does therefore facilitate reuse.

These additions to the current Ecodesign Directive further prolong the lifespan of products including PV panels and contributes to CE. It can be discussed if these new requirements are comprehensive enough. Forti [2022] emphasises:

"It is important to do as for all other electrical products, where the EU has come up with a requirement that they must be repairable, and it must be possible to replace all components. (Ed. for the PV industry) the same must apply.".

This statement substantiates that the proposal for the new Ecodesign Directive and the specific requirements suggested for PV panels can contribute to easier reuse of the panels as these include requirements regarding repairment. Even though it is essential to look into reuse of panels, Stenstrøm [2022] does stress that it is just as important to consider using the right materials to ensure a long lifespan of the panels and easy disassembly:

"With the establishment, it is also about choosing the materials that do not necessarily have to be reused, but which have a long life. We also need to think about how easy it is to disassemble the panels again..

This aspect contributes to the circular strategy *Design for easy dis - and reassembly (p)* by Konietzko et al. [2020b]. This entails that there already are considerations in the PV industry which align with circular product strategies within slow. However, it can be argued that these incentives on the product contribute to furthering reuse but it is still essential that the actors prioritise this as it is not required in the proposed requirements.

However, the new requirements neglect an aspect that is emphasised by several of the respondents which is a standardisation of the size. Hornbeak [2022] explains that they require a certain size and design in order to reuse these due to the tracks they use for their products. Hornbeak [2022] follows up: *"It is far from all PV panels that have the same size"*. Here, Forti [2022] and Harboe-Jepsen [2022] both mentions standardisation of the PV panels as a solution.

7.1.2 Standardisation of PV panels

This recommendation focuses on utilising standardisation of PV panel sizing across the EU which is inspired by the slow strategy *Design for standardisation and compatibility (p)* by Konietzko et al. [2020b]. Standardisation is central in terms of circular design [EMF, 2015] as this creates a common design that enables components and products to be compatible. Harboe-Jepsen [2022] elaborates that uniformity makes it easier to reuse parts of the panels. Forti [2022] agrees with this as he argues that standardisation would make reusing and recycling more efficient in the future when larger quantities occur. In continuation hereof, Forti [2022] emphasises that it would make it easier to automate all the phases and make the transportation more efficient. The recommendation is therefore that the PV industry needs to agree on a standard size in order to realise this circular strategy. Furthermore, there needs to be implemented a standard with requirements for testing reused panels and appertaining efficiency requirements. This will accommodate the concern presented by Lempkowicz [2022] regarding lack of legislation that ensures the quality of reused panels. However, it can be a challenge to have a standard size for the PV panels as these are both roof-mounted and ground-mounted which creates different demands on the sizes. Here, Forti [2022] suggests having two different standard sizes of PV panels. As opposed, this may cause a barrier if a large amount of ground-mounted panels have different size but needs to be reused as roof-mounted.

7.2 Business model

The product principle for slow solely focuses on the PV panels and how they can be designed to prolong their lifespan. However, it is important to involve the actors to achieve a longer lifespan and prolong through reuse. Therefore, the following section suggests recommendations based on the business model principle. As described in section 4.2, the strategies within the business model innovation principles have a broader perspective than the product principle as it targets the value creation of the firm and not only the individual product.

This section includes recommendations for three business models, which focus on different actors in the value chain of PV panels. The first two recommendations focus on the developers and importers of PV panels with a starting point in the companies Better Energy and Ennogie. These companies are used since knowledge about these companies has been obtained through the conducted interviews. The reason for focusing on these actors is because they have the responsibility for managing the waste according to the WEEE Directive. Further, as described in section 5.1, these actors operate on different markets with different business models, which entails that the recommended business models may not work for both markets. The last business model recommendation focuses on the collective schemes since they are managing the current EEE waste stream including PV panels and are therefore important to include.

The following recommendations try to solve or minimise the barriers; lack of economic feasibility and limited focus/knowledge on reuse of PV panels, which is identified in section 5.2.

7.2.1 Leasing

This recommendation focuses on the importers that are selling B2C on a smaller scale market (as described in section 1.1) and the developers that are using the business model divestment. Currently, in the B2C market and with divestment the panels are sold and the ownership is handed over to the consumers or other companies. This does not necessarily increase the lifespan of the panels or ensure reuse. Therefore, this recommendation suggests leasing as en possible solution. The recommendation is inspired by the slow strategy *Provide the product as a service (bm)* by Konietzko et al. [2020b].

With the use of leasing, the importers are offering the PV panels as a service and thereby keeping the ownership of the panels within the companies. This creates an incentive to increase the PV panels' lifespan. Furthermore, leasing keeps the panels in the inner loop of the technical cycle presented by EMF, see section 4.1. To unfold this circular strategy, the companies need to change their current business model. Instead, the business model should focus on providing PV panels or sustainable electricity as a service. This entails that the companies need to change from short-term business cases to long-term value creation. In the circular strategy for leasing, the companies maintain the ownership of the PV panels and are responsible for delivery, maintenance/repair, and take-back after the end-use phase at the customers [Agrawal et al., 2021]. In continuation of this, Harboe-Jepsen [2022] states that: *"What is important here is not just to extend the lifespan, but also to extend the service life."*. Because the importers retain the ownership throughout the PV panels' life cycle they can extend the useable life, recover them for reuse or recover value by reusing components for repair or manufacturing of their PV panels. This can contribute to maximising the economic utility of the PV panels while minimising the environmental impact since the PV panels and their components keep circulating Agrawal et al. [2021]. Therefore, this business model recommendation will require changes in the mindset of the companies.

Additionally, different products have certain characteristics that define the difficulty of incorporating circular use. It is for instance the aspects of complexity and the functional life cycle of a product. A PV panel can be characterised as a complex product as it has a complex value chain with a lot of different actors involved from production to EoL treatment. Furthermore, the PV panel has a long functional life cycle of 25-30 years. The long functional life cycle encompasses that circular agreements, like leasing, can be difficult to establish since the PV panels remain usable for a long period [Oppen et al., 2018]. There are risks and uncertainties with the use of long contract periods. Based on Oppen et al. [2018] effective agreements regarding circular use have a maximum functional life cycle or a contract period of 10-12 years. This entails, that it can be difficult for companies to establish leasing contracts for the entire lifespan of a PV panel.

Moreover, this recommendation will not solely require changes in the companies, but also the buying habits of consumers need to change. However, it can be difficult to change these buying habits because it is based on norms and institutions, but it is possible to alternate these [Axon, 2017]. The use of leasing is seen and used in other sectors such as the car industry. This implies that the leasing business model has been possible to implement among the consumers. Another aspect that can challenge the implementation of leasing is, that the private PV panels are already reused and sold on different platforms like DBA, Facebook's marketplace or through demolition companies if they are functional [Kristensen, 2022]. However, this is still on a small scale due to the low amount of decommissioned PV panels.

7.2.2 Individual Producer Responsibility

This recommendation focuses on developers who work with large-scale PV farms, and who own the farms and panels.

The individual producer responsibility is proposed because this could provide an incentive to reuse the panels or recover value from the collected end-of-use PV panels by reusing the components for new PV panels or using the components as spare parts for the in-use PV panels as presented for the leasing model for B2C importers. This could ensure more reuse since the PV panels are not sent to a collective scheme for waste management but instead there have been some considerations and evaluations of the PV panels. Furthermore, Forti [2022] from Ragn-sells states that:

> *"I could imagine that when they (ed. solar farms) are dismantled, they will never come back to us (ed. Ragnsells). I am almost certain that the manufacturers are making a scheme where the solar cells go back to their production. There will be such a large amount of a homogeneous product that they can benefit more from the value of the PV panels than we can".*

This statement accentuates the value that the developers can obtain by taking a stand on their used panels instead of only using the collective schemes for the waste management. In continuation hereof, Harboe-Jepsen [2022] stresses that there would be an economic incentive and a business model regarding reuse from the solar farms even if it is only 10% of the decommissioned panels can be reused due to the high amount of installed panels at the solar farms. This statement emphasises that the barrier of lack of economic feasibility could be overcome by this recommendation. Additionally, Stenstrøm [2022] pointed out that: *"It is a serious matter to take down a solar farm. So, if we can leave it for 20 more years, then it's just money in our pockets."*. This further, highlights the economic incentive for the developers to increase the lifespan of the PV panels.

One of the issues raised by a proposal for individual producer responsibility is the risk that if the developers are not part of a collective system. This means there is no financial assurance for the waste disposal of panels that cannot be reused or used as spare parts. However, Stenstrøm [2022] states: *"Funds have been set aside for decommissioning the farms. Even if we go bankrupt, those funds still exist. That is our responsibility."*. This emphasises that Better Energy is aware of their responsibility and that waste management has been contemplated.

Additionally, the LCA results regarding the annual degradation rate in figure 6.6 showed that the PV panels can potentially have a longer lifespan than 30 years and still have 80% of the efficiency with a degradation rate of 0,6%. This is backed by Better Energy's

ESG report, which states their panels have a lifespan of 50 years, and on the Danish PV Association's website, they are promoting a lifespan of 35 years [Better Energy, 2021; DSF, 2022]. This indicates that PV panels can potentially have a longer lifespan than the expected 30 years. However, this entails a need for longer contract periods for the solar farm areas to ensure the PV panels remain as long as they are usable. The current contract period is approximately 30 years Stenstrøm [2022].

7.2.3 Collective Reuse Schemes

Another business model recommendation which can be seen as an additional aspect of the aforementioned business models, is to integrate a reuse dimension to the exciting collective schemes. This recommendation is focused on the collective schemes which manage decommissioned PV panels. This recommendation is endorsed by Lempkowicz [2022] who states:

"The next process is to test all the panels that enter the waste industry, to see if they are still working quite well so we can put it aside for a reuse market. This is going to be the future."

This recommendation could ensure that the reusable panels are sorted out and reused instead of recycled as the current waste management system focuses on. The implementation of this requires a testing process of the panels to test their performance and functionality and an actor to re-sell the panels afterwards. Further, it can be argued that not all importers and developers have the capacity or knowledge to implement the aforementioned business models; Leasing and Individual Producer Responsibility. Therefore, this integrated system could contribute to ensuring reuse of PV panels. However, Forti [2022] predicts that this will only address the private generated PV panel waste because, as mentioned in the recommendation for individual producer responsibility, the developers will benefit from taking their own panels back.

Moreover, Harboe-Jepsen [2022] and Forti [2022] stress that there are existing reuse, repair, and refurbish systems of other electronic waste fractions such as computers. This indicates that there are some experience and knowledge to gain from these systems. However, challenges remain. With an integrated system that focus on reuse, the transportation and dismantling processes have higher demands than in the current system. As an example of this demand, Ennogie experienced a relatively high discard rate of the reused PV panels they bought due to poor handling in the dismantling and transportation processes [Hornbeak, 2022]. This underlines the additional need to focus on these processes in order to ensure further reuse. An additional challenge that complicates the implementation of this recommendation is the lack of a market for reuse. There are no actors that exclusively work with reuse of PV panels yet. All the work is on a testing and exploratory stage both in Denmark with Ennogie and in the EU where e.g. Supportive has started the investigating reuse of PV panels. One of the reasons behind this is the missing critical mass of used PV panels which is necessary to create an economic incentive to form a business case out of this fraction [Harboe-Jepsen, 2022]. However, it can be argued that the critical mass will increase in the coming decades which can create an economic incentive to further reuse and the development of business models within the field.

7.3 Ecosystem

This section elaborates on the ecosystem innovation principle as this is deemed essential in the transition towards CE. As opposed to the business model principle, the ecosystem principle consider the business models of not only the focal firm but also the actor interacting with this firm to achieve a common outcome [Konietzko et al., 2020a]. In order to suggest specific ecosystem strategies, it is necessary to identify and include the involved actors' business models and their appertaining networks. However, this is comprehensive, and a thorough mapping of the included actors has not been conducted in this study. Yet, it is still considered relevant to suggest recommendations within the ecosystem as this can help to accommodate the barrier: limited focus/knowledge on reuse of PV panels, which is pointed out by all of the respondents.

Generally, it can be deduced that the actors have different aims in their business models which are associated with what they "produce". Here, Better Energy aims at establishing solar farms and generating renewable energy as they are developers [Stenstrøm, 2022]. In opposition, the collective schemes strive to establish collaboration with developers and waste operators to ensure proper EoL treatment [Frahm, 2022]. Therefore, it can be argued that the actors have different interests due to their business models. According to Konietzko et al. [2020b], it is essential that the actors aim for a common goal in the ecosystem principle. However, reconciling a common goal with the actors' individual business models can be difficult, making the ecosystem principle complex. Currently, the regulation works as a common framework for the actors. The regulation is an essential aspect to support EoL treatment across the different actors in the supply chain. However, the current system which is based on the regulation and the extended producer responsibility does not require or encourage knowledge sharing among the actors. The system is generally built on an exchange of money for a waste management service of the PV panels. Therefore, these recommendations aim at fostering a collaboration and knowledge sharing among the actors and seek to minimise the barriers; limited focus/knowledge on reuse of PV panels. It is essential to further collaboration and knowledge sharing between the actors in order to reduce the environmental impact [Ramsheva et al., 2020]. The actors within the EoL treatment of PV panels can be defined as an ecosystem as they:

- consist of multiple entities that do not belong to one specific organisation, since the recommendation will enhance the actors to work towards a common goal together.
- involve local, regional, and global collaborative relationships as the actors will need to expand their network to change their focus to reuse
- imply flows of PV panels, knowledge, money, etc.
- involve complementary products and services since the different actors contribute to the ecosystem with different aspects to further reuse.
- evolve as actors; Working together to enhance and further reuse, the actors may need to redefine their position or business model.

7.3.1 Collaboration - Collective schemes, waste operators and reuse/recycling operators

This recommendation focuses on the collaboration between the collective schemes, waste operators, and reuse/recycling operators. The realisation of this strategy rests on the establishment of collaboration that furthers knowledge sharing. Increasing the knowledge shared among the actors would enable to development of systems that ensure better reuse of PV panels. By increasing the collaboration and knowledge sharing it is possible to establish the common goal of furthering reuse of PV panels across the supply chain which is essential in order to realise CE. Furthermore, this recommendation could help to expose uncertainties and challenges along the supply chain [Ramsheva et al., 2020]. Especially, Frahm [2022] emphasises the importance of these collaborations in order to reach CE as he explains:

"We collaborate with Ragn-Sells regarding how we operate. In order to identify better (Ed. EoL treatment) solutions, it is relevant to utilise each other's network.

Additionally, Frahm [2022] points out that longer contracts further the development of competencies for both parties through the collaboration and enable that they thereby can help each other. This recommendation is moreover highly dependent on the trust among the actors. This is a central element in order to cooperate across the supply chain [Konietzko et al., 2020a]. Konietzko et al. [2020a] argues that trust helps to keep the actors pursuing the same goals which are important in the ecosystem principle. This is further exemplified by Forti [2022] where he explains that they have recently started their collaboration with Supportive in Germany. Supportive have recently started to investigate refurbishment of PV panels. In this regard, Forti [2022] stresses that they want to support the investigation of refurbishment of PV panels which is why they have initiated this collaboration. Even though Supportive is new in the field of reused PV panels, Ragn-Sells put their trust in them and want to support this development.

7.3.2 Collaborations - developers and reuse companies

This recommendation takes departure in Ennogie's experience. As described in section 5.1, Ennogie experienced that 1/3 of the panels broke during the transportation from Germany to Denmark. Furthermore, they experience that the panels were ruined due to the cables being cut too close to the junction box on the back of the panels which is why they had to discard these panels [Hornbeak, 2022]. Increasing the knowledge and experience sharing between the developers, who are responsible for taking down the used panels (developers), and the reuse companies enable to solve issues such as these. Hornbeak [2022] elaborates: *"Here, relatively few measures are needed to be able to minimise the waste"* and suggests that *"an agreement with the farm owners how "best practice" is to take down the cells"* can help to solve the problem of the discard rate. Here, the reuse companies (Ennogie) could share their experiences with developers in terms of buying reused panels and how these need to be handled both during the dismantling and the transportation in order to lower the discard rate. Another issue, increased knowledge sharing could help to accommodate is the transportation. Here, Ennogie has tested transportation of the panels vertically in the lorry and experienced that this is the optimal way to avoid damaged panels [Hornbeak, 2022]. Sharing this information with the developers could furthermore lower the discard rate during transportation.

Furthermore, contracts can be used to establish requirements for the reused panels. Harboe-Jepsen [2022] gives an example hereof in terms of refurbishment of computers

"There we use contracts where it is important for us to make sure that there is a warranty, repairment, traceability (ed. on reused computers). This can also be used in the collaborations in the PV industry to ensure the quality of the reused panels and thereby accommodate the barrier regarding lack of quality of reused panels pointed out by Lempkowicz [2022].

7.3.3 Collaboration with externals

Another recommendation is a general collaboration with external actors outside the PV industry. Ennogie has collaborated with students [Hornbeak, 2022]. By collaborating with knowledge institutes and students it is possible to obtain the newest knowledge regarding the reuse of PV panels. Additionally, Better Energy has set up a committee in which actors within the regulative framework, lobbyists, and technical actors participate [Stenstrøm, 2022]. This collaboration helps to affect and set up new requirements. Based on this, it can be recommended that collaboration with actors beyond the EoL treatment of PV panels can contribute with new knowledge and different aspects that can help to further reuse of PV panels.

The aforementioned recommendations aim at furthering reuse of PV panels through collaboration. It does, however, enhance the individual actor's workload. This requires the actors to devote time to these collaborations, which can lead to conflict if the individual actors do not achieve anything for their respective enterprises. Therefore, it is important to create a common goal. On the other side, it can also be argued that the PV industry is not ready to invest time and money in furthering reuse due to the lack of focus and lack of decommissioned panels.

7.4 Sub-conclusion

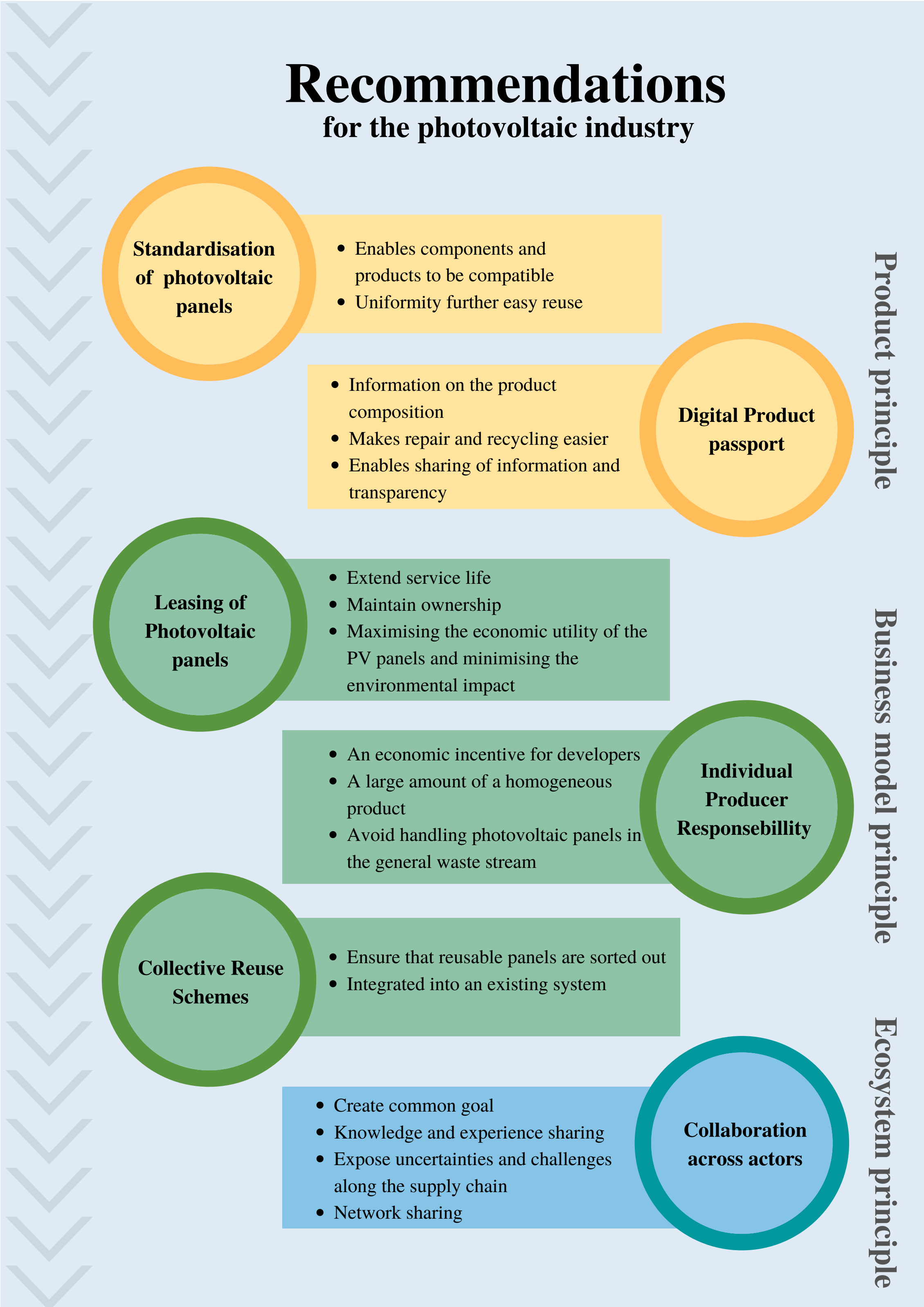
In summary, the suggested circular strategies have the potential to realise CE for the PV industry. To answer the third sub-question, circular strategies are conducted in the three innovation principles; product, business model, and ecosystem within the slow strategy. This is done as it is necessary to consider the three levels in order to realise a CE transition for the PV industry. The aim of minimising the barriers, pointed out by respondents, have been the foundation for the circular strategies. Furthermore, appertaining recommendations are suggested which is done to support to the different actors in the PV industry in the realisation of CE. Table 7.1 summarises the circular strategies and which barriers these accommodate.

Innovations principle	**Circular strategy / recommendation**	**The barriers the recommendation minimise**
Product	Standardisation	Lack of design that further reuse and limited focus/knowledge on reuse of PV panels
	Digital Product Passport	
Business model	Leasing	Lack of economic feasibility and limited focus/knowledge on reuse of PV panels, which is identified in section
	Individual producer responsibility	
	Collective reuse schemes	
Ecosystem	Collaboration - Collective schemes, waste operators and reuse/recycling operators	Limited focus/knowledge on reuse of PV panels
	Collaboration and knowledge sharing between developers and reuse companies	
	Collaboration with externals	

Table 7.1. Summary of suggested circular strategies and which barriers these help to minimise

All of the suggested strategies will further the focus and knowledge on reuse of PV panels. This can be derived as the current focus and knowledge is highly centred around recycling. Therefore, increased work with reuse of PV panels will generate experiences and knowledge which will be obtained in the industry. Especially, the circular strategy within the Ecodesign principle will support knowledge and experience sharing. The strategy within the product principle solely focus on the design of the product. The recommendation of standardisation will support realising reusing PV panels as the panels and components will become more compatible. The strategies within the business model principle will accommodate the barrier regarding economic feasibility as these strategies aim at creating a business models which centres around reuse. Therefore, reused PV panels become part of their way of earning money. The suggested circular strategies and recommendations do therefore support the realisation of CE in the PV industry by operating at different levels from product to ecosystem.

A visual representation of the recommendations is presented on the following page. Here, the benefits which support realising reuse in the PV industry is highlighted within the various recommendations.


Recommendations
for the photovoltaic industry
Standardisation of photovoltaic panels
Enables components and products to be compatible
Uniformity further easy reuse
Information on the product composition
Makes repair and recycling easier
Enables sharing of information and transparency
Digital Product passport
Product principle
Leasing of Photovoltaic panels
Extend service life
Maintain ownership
Maximising the economic utility of the PV panels and minimising the environmental impact
An economic incentive for developers
A large amount of a homogeneous product
Avoid handling photovoltaic panels in the general waste stream
Individual Producer Responsebillity
Business model principle
Collective Reuse Schemes
Ensure that reusable panels are sorted out
Integrated into an existing system
Create common goal
Knowledge and experience sharing
Expose uncertainties and challenges along the supply chain
Network sharing
Collaboration across actors
Ecosystem principle

8 Discussion on choices and methodical delimitations

This section includes reflections on some of the choices and methods used in this study. This entails a discussion of why the proposed recommendations are focused on reuse and how this may affect this study's findings. Furthermore, the literature review is discussed in terms of how it is carried out. The use of the method; interview is also included in the discussion, which encompasses a discussion of the chosen respondents and how the output of the interviews has affected the results of the study. Finally, the LCA method is discussed regarding the methodical considerations.

8.1 Choice of reuse focus

This section includes a discussion of the chosen focus on reuse rather than recycling. The focus on reuse for the circular strategies was based on the results of the conducted LCA where the reuse scenario indicated a significant benefit for the environment compared with recycling. However, the recycling scenario likewise showed benefits for the environment. Therefore, recycling could have been included as well. Furthermore, the industry has an increased focus on recycling since it is a "new" waste fraction due to the current low amounts. Another aspect, that is important in the discussion regarding whether recycling should have been included, is the identified barriers. Based on the knowledge gained from section 5.2, it is evident that there are several barriers related to recycling. Moreover, more barriers have been identified to recycling than reusing. Therefore, it can be argued that these barriers indicated a need for further investigation and focus on recycling as well.

Additionally, it is important to emphasise that recycling is an important aspect to consider since not all the used PV panels are reusable at the EoL. Harboe-Jepsen [2022] also stresses in this regard that:

"What is important here is not just to extend the lifespan, but also to extend the service life. So, if we get something reused, then it should be used properly. If not, it is better to get the materials recycled.".

This highlights the need for both reuse and recycling within the treatment of PV panels. Further, some repairers have also investigated the reuse of subcomponents from the PV panels such as the aluminium frame. The frame can be remanufactured and used for other things like a light fixture [Harboe-Jepsen, 2022]. This aspect of remanufacturing could also have been important to consider in the proposed circular strategies. This indicates that the treatment of PV panels is not fixed to one solution or treatment approach, but the transition to CE requires an integrated system of both reuse and recycling. Therefore, could it be beneficial to include the recycling aspect simultaneously. However, reuse should be prioritised due to environmental benefits, which is why furthering reuse is the primary focus of this study.

8.2 Literature review

By investigating the field of this study in-depth, the results of the state-of-the-art, see section 1.4, can be reflected upon. Through the research, the study has been narrowed down to exclusively focusing on *recycling* and *reuse* as this was the main focus of the interviews. Therefore, the search string could have been narrowed down to include recycling and reuse which would have excluded literature focusing on alternative waste treatment opportunities. Additionally, the study includes the focus of CE which is not included in the search string. It can therefore be discussed whether there is a "gap" between the investigated field and the SOTA as this entails a risk of excluding articles that focus on the CE. A way of strengthening the SOTA could have been to use two separate search strings; one focusing on LCA of recycling and reuse and the another focusing on CE, recycling, and reuse. The scope of the literature may have been narrowed in terms of the specific topics of CE and LCA by utilising two distinct search strings. Furthermore, it could be argued that combining both features in a single search string risks excluding relevant literature. However, the results of the SOTA do still contribute to the field as these show the limited focus on reuse and emphasise the current focus on recycling. Furthermore, the results indicate that limited LCAs have been conducted on the EoL treatment of PV panels.

8.3 Interview

In terms of the interviews conducted, it is relevant to reflect upon the included respondents and the questions asked.

8.3.1 Selection of respondents

In the identification of relevant respondents, the aim was to identify actors that are related to the EoL treatment of the PV panels. However, the respondents included do not participate in the same supply chain as e.g. Ennogie works with reuse whereas Better Energy focuses on recycling. These different aspects involve different actors throughout the supply chain. It could therefore have been relevant to base the study on one actor and their network as this would make it easier to suggest circular strategies for the specific ecosystem. However, including actors that are not in the same supply chain creates an opportunity to get different perspectives on the topic which enables for a more versatile insight into the industry and the challenges they are facing. Furthermore, it is deemed relevant to include both Ennogie and Better Energy, as Ennogie serves as a pioneer for creating a business model based on reusing panels which can be the inspiration for large-scale developers such as Better Energy.

8.3.2 Interview questions

As elaborated upon in the SOTA, in section 1.4, the terms reuse and recycling are used somewhat interchangeably. This was also emphasised during interviews with the respondent. Here, the use of recycling and reuse were mixed. This was furthermore due to the formulation of the questions regarding the barriers as the two terms were both included in this. By analysing the interviews, it was clear that recycling was the technology most of the respondents referred to. Therefore, it was difficult to separate when the focus was on recycling contra reuse.

8.4 Life cycle assessment

This section includes a discussion of the conducted LCA and the methodical considerations. An aspect that is relevant to discuss is that the quantitative parameters cannot be included in LCA which includes trade-offs. Reusing PV panels require more man-hours compared to recycling as the panels need to be handled more carefully when they are taken down so they do not break. Furthermore, reusing requires that the panels are cleaned and tested which increases the workload. These are aspects that cannot be included in the LCA but may have an influence on the decision-making process.

Another aspect is related to data and modeling hereof. In section 1.4 it was found that the LCA studies of EoL treatment of PV panels are limited which emphasises the limited focus hereof. Therefore, this study contributes to this field by investigating the environmental impacts of recycling and reusing c-Si PV panels. Due to the limited focus on EoL and the few LCA studies conducted, the foreground data used for the LCA is secondary data based on existing literature as this was the data available. The limited primary data has also been identified as a barrier through the SOTA, see section 1.4. Using secondary data entails that assumptions had to be made which increases the uncertainties. It would therefore have strengthened the results of the LCA if the foreground data had been based on primary data from the actors involved. However, due to the limited knowledge in the industry, the industry has not yet specific data available for the processes of recycling and reusing PV panels which is why the data was difficult to get. A way of improving the study and strengthening the results could therefore be to use primary data from the specific facilities and processes e.g. the emission from the facilities and processes, the exact recycling rates from the recycling facilities, and data on testing and cleaning the panels. These information could have limited the need to use assumptions and thereby decreased the uncertainties.

Finally, the criticality of the materials used in the PV panels should be considered when conducting an LCA. As mentioned in the introduction, see section 1.2, there are certain materials that are particularly relevant to recycling and recovery due to their criticality. Urbina [2022] highlights the need to consider these critical materials beyond the LCA as the consideration hereof is not included in the standardised LCA. Even though the recycling percentage of PV panels is high and recycling entails environmental benefits, the criticality of the individual raw materials is not considered. This can also be considered as a critique of the targets in the WEEE Directive, as the targets do not demand that the criticality is taken into consideration in terms of recycling and recovery. Therefore, the criticality of the materials (e.g. bauxite in the aluminium production) should be evaluated upon, and what external aspects these affect [Urbina, 2022]. This is therefore an important aspect that needs to be considered in the recycling of materials from PV panels.

9 Conclusion

This research looks into waste management in the photovoltaic industry, with an emphasis on the circular economy and circular strategies for photovoltaic panel reuse. This study is vital to illuminate since use of photovoltaic panels are rapidly evolving and will continue to play a key role in the energy system. Nonetheless, the expansion results in an increase in waste, which must be appropriately treated to avoid a repeat of the issue with wind turbine blades, when waste management was deemed too late. As a result, it is thought necessary to examine photovoltaic panel waste management prior to the anticipated increase in waste volume on the market. Photovoltaic panels are currently recycled, recovered, and disposed, which corresponds to the three lowest levels of the waste hierarchy. However, there is limited focus on photovoltaic panel prevention or reuse, which are crucial parts of the circular economy. To investigate this, this study aims to answer the following research question:

What are the environmental impact of recycling and reuse of photovoltaic panels and how can further reuse be supported by actors involved in the end-of-life management from a Danish perspective?

To answer the research question different methods have been applied in a combination of quantitative and qualitative approaches. This mixed-method approach contributes to a broad understanding of the research field since multiple aspects and actors are important to consider in a waste management system that supports the transition to a circular economy. The primary methods used in this study are interviews with relevant actors involved in the end-of-life and life cycle assessment of a crystalline silicon photovoltaic panel.

The conducted interviews focused on the respondent's role in the waste management system and their experienced barriers regarding recycling and reuse of photovoltaic panels. Moreover, the actors' experienced barriers are compared with barriers found in the literature. Based on this it can be concluded that the current waste management of photovoltaic panels to a large extent mainly focuses on recycling as waste treatment due to the regulation in the Waste from Electrical and Electronic Equipment Directive. The photovoltaic panels are currently either stored in Denmark or shipped to Germany or Belgium for recycling and material recovery. Only smaller actors in the Danish waste management system have started to investigate and experiment with reuse of photovoltaic panels. Furthermore, by mapping the respondents' barriers, it was identified that the focus is generally on the barriers of recycling. It can be derived that the industry for recycling is far more advanced than reuse which is still a new and unknown field within the industry.

The conducted life cycle assessment focuses on the different end-of-life scenarios; recycling and reuse for a crystalline silicon photovoltaic panel. The crystalline silicon panel has been chosen as an example of a photovoltaic panel. This type is chosen since it is the most dominant type used worldwide and is also assessed to be in the the coming decades. The conclusion, based on the conducted life cycle assessment, is that reuse is a significantly better solution for the treatment of photovoltaic panels compared to recycling. The reuse scenario is better in all the investigated midpoint categories. However, both scenarios would benefit the environment. Based on the sensitivity analysis of data input, it can be concluded that aluminium and silicon causes the largest impacts on the recycling scenario. For the reuse scenario, it can be concluded that the substituted energy have the greatest impact on the environmental performance of this scenario. Furthermore, the degradation rate has an influence on the lifespan if the efficiency should not be lower than 80%. Therefore, it can be derived that the panels potentially have a longer use phase than the estimated 25-30 years. Based on the conducted life cycle assessment, it can be concluded that the focus within the photovoltaic industry should be on reuse due to the environmental benefits.

Recommendations have been made to encourage reuse of solar panels towards the end-of-life. These recommendations are based on the slow strategy by Konietzko et al. [2020b] and aims to minimise the experienced barriers identified by the actors involved in the waste management. Additionally, recommendations for the three innovation principles of product, business model, and ecosystem have been proposed, as they are all key issues to consider in the transition to a circular economy. The product principle recommendation standardisation will facilitate reuse by increasing the compatibility of panels and components. The three business model recommendations; Leasing, Individual Producer Responsibility and Collective Reuse Schemes will provide an economic incentive for different actors to focus on reuse, implying that increased reuse will benefit multiple actors. Finally, the recommendations, which are based on collaboration among the different actors, will help to promote reuse by accommodating the barrier of limited focus and knowledge. It can be concluded that the suggested recommendations will further the focus and knowledge on reuse of photovoltaic panels.

To answer the research question, it can be concluded that both recycling and reuse of photovoltaic panels entail environmental benefits. Furthermore, it can be concluded that the suggested recommendations within the slow strategy can support the actors in furthering reuse of photovoltaic panels in Denmark.

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A Appendix

A.1 List of peer-reviewed literature

Table A.1

Title	Country	Reference
Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico	Mexico	[Santoyo-Castelazo et al., 2021]
Comparative life cycle assessment of end-of-life silicon solar photovoltaic modules	Switzerland	[Lunardi et al., 2018a]
A scientometric review of trends in solar photovoltaic waste management research	Australia	[Oteng et al., 2021]
Life cycle assessment of recycling strategies for perovskite photovoltaic modules	USA	[Tian et al., 2021]
Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England	England	[Li et al., 2018]
Life Cycle Analysis for the Feasibility of Photovoltaic System Application in Indonesia	Indonesia	[Yudha et al., 2018]
Overview for end-of-life crystalline silicon photovoltaic panels: A focus on environmental impacts	Korea	[Seo et al., 2021]
A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	Italy	[Ansanelli et al., 2021]
Management of end-of-life photovoltaic panels as a step towards a circular economy	Italy	[Sica et al., 2018]
Environmental impacts of solar-photovoltaic and solar-thermal systems with life-cycle assessment	Australia	[Mahmud et al., 2018]
Recycling and recovery of perovskite solar cells	USA	[Liu et al., 2021]
Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery	Belgium	[Duflou et al., 2018]
Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders	Belgium	[Peeters et al., 2017]
Sustainable recycling technologies for Solar PV off-grid system	Germany	[Uppal et al., 2017]
Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels	Italy	[Vellini et al., 2017]
Multi-levels of photovoltaic waste management: A holistic framework	Australia	[Mahmoudi et al., 2021]
A feasibility assessment of photovoltaic power systems in Ireland; a case study for the Dublin region	Ireland	[Murphy and McDonnell, 2017]
End of life analysis of solar photovoltaic panel: roadmap for developing economies	Ghana / Finland	[Ndzibah et al., 2021]

Exploring Secondary Markets to Improve Circularity: A comparative case study of photovoltaics and hard-disk drives	USA	[Watts et al., 2022]
Application of LCA to Determine Environmental Impact of Concentrated Photovoltaic Solar Panels—State-of-the-Art	Poland	[Ziemińska-Stolarska et al., 2021]
Life Cycle Assessment of Disposed and Recycled End-of-Life Photovoltaic Panels in Australia	Australia	[Daljit Singh et al., 2021]
A Systematic Literature Review of the Solar Photovoltaic Value Chain for a Circular Economy	Switzerland	[Franco and Groesser, 2021]
End-of-life photovoltaic modules: A systematic quantitative literature review	Australia	[Mahmoudi et al., 2019]
The environmental and economic impacts of photovoltaic waste management in Thailand	Thailand / USA	[Faircloth et al., 2019]