Supply Chain of Second Life PV Modules for Reuse in Europe

INVESTIGATING CIRCULAR SERVICE MODELS FOR SOLAR POWER INDUSTRY

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Abstract

The transition to low-carbon energy technologies like solar photovoltaic (PV) brings a range of practical challenges for end-users, supply chain actors, and society. As the deployment of the technology is rising, the projections suggest that an increasing volume of PV modules are decommissioned well before reaching their end of technical lifetimes. While recycling or landfilling are preferred as the current fate of decommissioned PVs, the functional modules could still be introduced into a second life, following the circular economy strategies such as reuse, repair and repurpose. However, the current second life market exists as a niche and is considered unattractive for several reasons. Despite a growing interest in PVs and circular practices, there is a lack of empirical research about the large-scale development and implementation of new markets dedicated to the second life of PVs. In order to assess the reasons for the slow adoption in a holistic way, the study visualises the activities governing the supply chain of second life PVs. With the intention to consider the different perspectives and interrelated business models, the study centres on the activities which slow the resource loops in the circular economy framework. Using semi-structured interviews with relevant experts in the EU landscape, the study adds to (and draws on) the limited available literature on second life PVs. The mapping of material, information and monetary flows between the activities is used to explain the current situation, the notable drivers, constraints and possible solutions for advancing the circular agenda. The findings indicate that (i) financial viability for both the supply and demand side, (ii) legal regulations, (iii) operational aspects and (iv) market acceptance limit the development of second life activities in the EU. Three enabling recommendations are put forward. Firstly, an advancement in the legal regulations and incentives regarding second life activities can give a qualitative boost to the overall sector. Secondly, an increase in collaboration between the different actors can reduce the significant cost factor in the supply chain, i.e., reverse logistics. Thirdly, a positive change in the perception concerning second life can create desirability of second life PVs among the entire supply chain. Overall, the study underlines that interventions beyond the company level are key to achieving a circular economy in the solar power industry and its intended goals.

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Abbreviation and Glossary

BOS	Balance of System
EPR	Extended Producer Responsibility
GHGs	Greenhouse Gases
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Energy
SDGs	Sustainable Development Goals
WEEE	Waste Electrical and Electronic Equipment
EoL	End of Life

In this study, EoL modules are assumed not only with physical properties loss but also possible trigger from economic framework circumstances like the end of feed-in tariff period or incentive to replace modules with more efficient units.

PV	Photovoltaic

PV is a technology to harness solar energy using photovoltaic cells. In this study, the term PV should not be confused with concentrated solar power (CSP). PV modules are used to denote both PV modules as well as PV panels, while PV systems form the total combination of PV modules with other components necessary to complete the power generation to a usable form.

Second life

In this study, second life implies re-introduction into the market through reuse, repair, resell and repurpose activities, unless otherwise stated.

1. Introduction

In the quest for transitioning to clean energy systems, the global priorities are changing from conventional fossil fuels to a dependency on critical minerals such as copper, lithium, cobalt, nickel and rare earth elements (IEA, 2021). New developments in the technologies require a wider assortment of materials (Greenfield & Graedel, 2013) and overall demand for material is projected to increase with time (Elshkaki et al., 2018). Every year, technologies like solar photovoltaics and wind turbines are being deployed significantly to reduce our dependence on conventional power plants and gradually phase them out. As the policy targets to reduce our greenhouse gas emissions are coming closer (European Commission, 2019), the developments in green technologies are reducing the prices of low-carbon energy generation (IRENA, 2020). The pressure exerted on the mining industry is also escalating with higher resource demand for modern technologies. As mining cannot be sustained and negatively affects our society and environment (Sonter et al., 2020) (Norgate et al., 2007), efficient material resource management for clean energy technologies must be the priority, and the relevant actors should drastically reduce leakages from the supply chain. Unlike the current "take-make-waste" system, a circular economy provides a way to rethink the supply chain and utilise fundamental changes for closing material loops and avoid material leakages (Ellen MacArthur Foundation, n.d.). When integrated with the tools like regulations and business models, the foundational principles of the circular economy can unlock the potential of resource efficiency, especially at the European level. This introductory chapter provides an overview of the research focus, its objectives regarding the research questions, and the target audience for the work.

The importance of energy generation for satisfying basic human needs is well emphasised by the Sustainable Development Goal 7 (SDG), which sets the objective to ensure reliable, sustainable, and modern energy for all. The goal places the driver for increasing renewable energy use to stabilise the atmospheric CO_2 concentration, closely related to SDG 13, to combat climate change and its impacts (United Nations, 2020). For the long-term goals related to climate change, low-carbon energy must become an inherent part of the sustainable energy mix. Solar energy is a vital source of renewable low-carbon energy and can provide a range of long-term benefits environmentally (IRENA, 2013). According to IEA (2011), the deployment of solar energy technologies can increase a countries' energy security, enhance sustainability, reduce pollution, lower the cost of mitigating global warming and keep the prices of fossil fuels lower. It is reasonable that the annual report *World Energy Outlook* from IEA (2020) set forth solar as the *"new king of electricity"* since it is likely to play the central role in the transition to clean energy systems.

Different technologies harness solar energy, of which solar photovoltaic (PV) systems have developed from a niche product to mature technology for mainstream electricity generation. PV technology is perceived as commercially mature, silent in operation and does not require moving parts (IRENA, 2013). The well-known Sustainable Development Scenario (SDS) from IEA's modelling exercise, consistent with the trajectory of the Paris Agreement, shows that the annual installation of PV systems needs to become threefold from today's levels by 2040 (IEA, 2020). Roughly two-thirds of the global greenhouse gas (GHGs) emissions arise from fossil fuel energy, which must reduce significantly in the energy transition (IPCC, 2014). Compared to coal power plants producing about 800 g CO_2 per kWh of electricity generated, PV systems are attributed to merely 30 g CO_2 per kWh (Louwen et al., 2015). In addition to the low carbon footprint, the ability of distributed set-up and modularity of PV systems is unmatched (Reinders et al., 2016), reflected by support from 130 countries in one form or another (IEA, 2020). Given the trends, the literature suggests that the PV industry has witnessed a sizable expansion since the early 2000s, which has become apparent in its lowering of the cost compared to other sources of electricity (Weckend et al., 2016) (Gielen, 2019). The mainstreaming of PV technology worldwide has resulted in a rapid decline in prices, demonstrating about a 32% reduction in cost per kWh for every doubling of capacity currently (IRENA, 2018).

Shakespeare’s words on ‘too much of a good thing” (Shakespeare & Furness, 1963) can apply to some extent in the case of deployment of photovoltaic systems as well. “Good things” like better accessibility and low cost of electricity generation have set the deployment rate of PV technology high. Such high deployment has generated concerns over the impacts of the system’s production (Norgate et al., 2007) and its afterlife after decommissioning (Lunardi et al., 2018). The manufacturing of PV modules is energy-intensive, demands (critical) raw material use, and involves environmentally toxic chemicals. The new development in the technology requires a wider assortment of materials than in the past (Greenfield & Graedel, 2013). The proper disposal after decommissioning is also a challenge since the industrial level recycling process are still under development. Early decommissioning of the PV modules for reasons like repowering only exacerbates the problem. Unless there is a way to introduce circular economy principles in the supply chain, the entire system would demand resource extraction and exert pressure on disposal activities. In a circular economy framework, extending a product lifetime can bring an overall positive economic impact, reduce environmental burden, and endure social benefits such as knowledge and skills generation (European Parliament, 2016). Similarly, the decommissioned PV modules with functionality earlier than can still be introduced in the market to extend their service lifetime. According to a study by European Parliament (2016), the actors organising activities such as maintenance, repair, rental services, second hand repurpose and resell are the most likely to benefit from the longer product lifetimes in the EU member states.

The positive effects of the circular economy will not be achieved unless the tools and activities required to achieve it reaches a sufficient scale in the supply chain. Like any solution in the context of the energy transition, the scale-up of circular economy practices for closing and slowing the material loops is a joint effort between different policy and industry actors (IEA, 2020). The coordinated movement of actors is shaped by a proper regulatory framework and support mechanisms from the government. However, as with any new technology or business model, the future perspective of second life PV modules seems blurred as the inflow of decommissioned modules is relatively premature. This lack of insight in terms of volumes and costs can affect the private sector investing in new applications and business models for second life PV modules. It can also involve public authorities in terms of decision making about the required regulations or supports. Since the literature and market activities on the second life PV modules are limited, it is essential to address the current knowledge gaps.

1.1 Aims and scope of the study

The overall goal of the research is to develop a complete overview of the current supply chain of second life PV modules for reuse in Europe. The study results identify the bottlenecks and required actions to develop a scalable supply of second life PV modules. Based on the knowledge gap, the main question for this research is: ***How can the supply chain of second life photovoltaic be developed within the EU to achieve circular economy goals?*** The following sub-research questions were formulated to answer the main research question:

RQ1: What are the major activities in the second life PV supply chain, and what are the respective roles of actors and stakeholders within the industry?

RQ2: What does the overall supply chain for second life PV look like regarding material, information, and monetary flow?

RQ3: What are the major drivers and bottlenecks in developing a successful second life market for PV modules?

The study was conducted with the support of VITO and the CIRCUSOL project consortium. CIRCUSOL is a Horizon 2020 innovation project which stands for “Circular Business Modules for the Solar Power Industry” and has 15 project partners from 7 European countries. These partners bring their willingness and expertise to develop and demonstrate business solutions for the circular economy in the solar power sector. The project started in 2018 with the Flemish Institute for Technological Research (VITO) as the project coordinator. The consortium partners of the project provided information, which is why the research questions are framed within the scope of Europe. Therefore, the export of PV modules outside of European member countries is not under the scope of this study. Due to time limitations, the scope of the study is limited to PV modules. The study does not consider the second life market for components and associated equipment.

The study aims that the results will further interest actors and researchers in the supply chain of solar photovoltaics in creating a circular PV industry. The targeted audience also encompassed industry organisations likely to identify business opportunities for second life photovoltaics. With this study, the aim is to fill these gaps to some extent which can provide knowledge for the further development of research and business models in this field. Lastly, the findings of this study can support policymakers seeking to remove the bottlenecks and implement enabling conditions for the new emerging opportunities to integrate circularity in the solar industry in the long run.

1.2 Outline of the thesis

The rest of this thesis document is organised as follows:

Chapter 2 develops a comprehensive review of the key concepts and theories on solar photovoltaics and concepts of circularity based on the academic literature and business reports.

Chapter 3 details the rationale and methodology used for conducting an explorative study using qualitative data collection and analysis methods. It describes the procedure to collect and analyse literature (academic and grey) and semi-structured interviews.

Chapter 4 presents the results of the research, which answers the first two stated research questions. The activities occurring in the supply chain of second life PV modules are described in detail, followed by an illustration of different flows in the supply chain.

Chapter 5 develops the main discussion points on the study's results, limitations, and policy recommendations. The first part of this chapter answers the third research question on identifying opportunities and barriers in developing the second life PV market. Key recommendations for the further activities and limitations of the overall study follow.

Lastly, Chapter 6 presents the main conclusions on the overall study by answering the main research question and highlighting the research contribution in second life solar photovoltaics.

2. Literature review on solar photovoltaics and circular economy

The chapter starts by introducing different types of solar PV technologies and their material dependence, followed by presenting the role played by their deployment and the significant consequences associated with it. A detailed analysis on EoL disposal options for PV modules follows, concluding with the concept of circular economy and the opportunities and challenges brought forward for its integration into the PV module supply chain.

2.1 Technologies and materials for the PV modules

Solar photovoltaic technology works on the principle of photovoltaic effect, discovered by physicist Edmund Becquerel in the 1830s (Rappaport, 1959) (Reinders et al., 2016). The photovoltaic effect refers to generation of an electric potential upon exposure of material to irradiance (Rappaport,1959) but the term is predominantly associated with the ability of semiconductor layers to harness solar energy (Reinders et al., 2016). Following the other discoveries like the properties of irradiance, the photoelectric effect, and the elementary charge of electricity (Reinders et al., 2016), it was only in the 1950s that the first silicon solar cells were presented by the Bell Laboratories with a conversion efficiency of merely 6% (Chapin et al., 1954).

The photovoltaic technology consists of cells with an active layer of semiconductor materials which transform the absorbed light into voltage or electric current (Reinders et al., 2016). These individual cells are also called solar cell or photovoltaic cell, which form the smallest power producing unit in a PV module. These cells are interconnected and encapsulated to form a solar module or PV module as illustrated in the Figure 2. A PV panel is one or more pre-connected PV modules. In this study, the terms PV module and PV panels are used synonymously. Furthermore, PV modules or panels connected into a complete power-generating unit is referred to as a PV array.

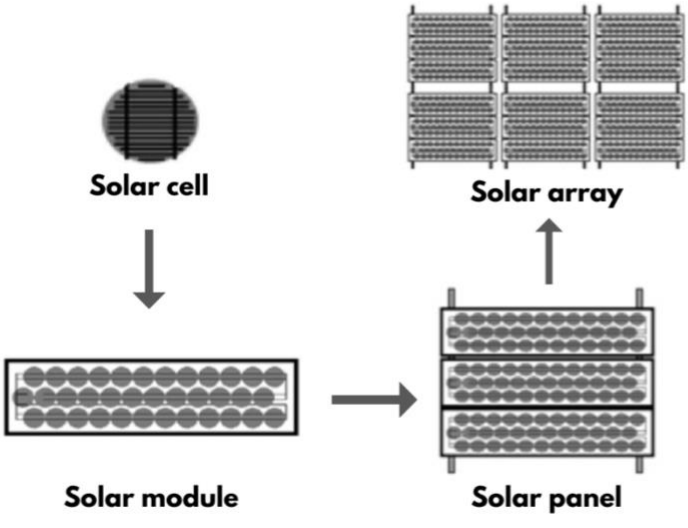

Figure 1. An illustration of a cell, module, panel and array of a solar PV system (author's elaboration)

PV module is the term followed throughout the study, and Figure 2 shows different layers which make up a typical PV module. The power generating layer of solar cells is sandwiched between different protective layers. A transparent glass is used for outer protection while allowing the irradiance from sun to transmit and reach the cells. Aluminium framing provides stability for the entire module and makes it a commercial product. For installation, a mounting structure is required for optimal orientation along with other components such as inverter and storage battery which form the balance of system (BOS). The function of inverter is to convert the direct current generated from PV modules to alternate current in order to supply electricity to the grid. The BOS include the components other than the PV modules including cabling and power control systems (IRENA, 2013).

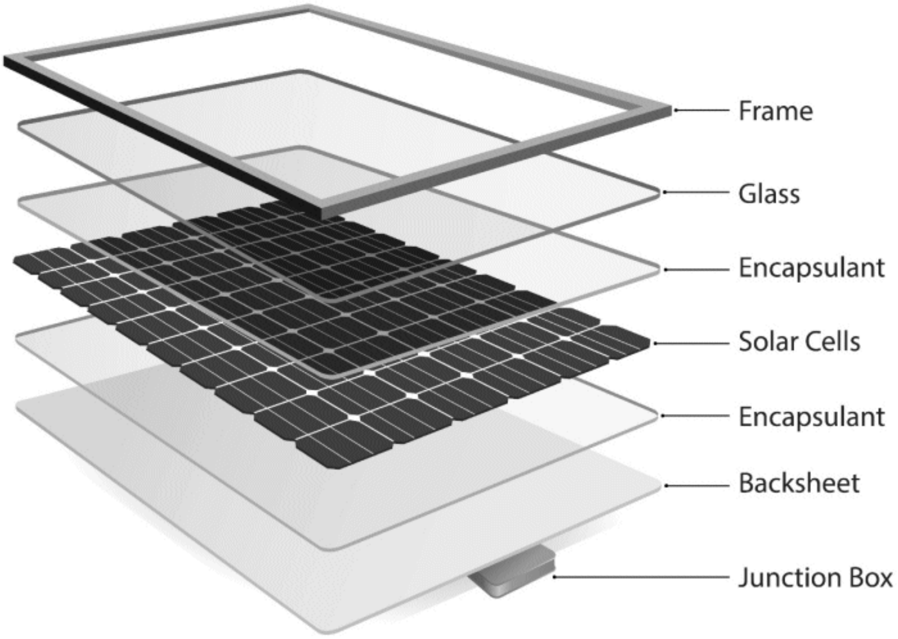

Figure 2. Schematic of solar panel and its layers, adapted from Kant et al. (2016)

Depending on the technology and size, PV modules are commonly rated between 290 to 500 W (IEA, 2020). The different types of PV modules differ according to their technology generations and the materials used in their manufacturing, as illustrated in Figure 3. The most widespread are first-generation technology which is based on crystalline silicon (c-Si) wafers (Ardente et al., 2016). The second-generation technology involves thin-film alternatives like cadmium telluride (CdTe), copper indium gallium di-selenide (CIGS) and amorphous silicon (a-Si). These are clustered into thin-film technologies because of their lower thickness compared with c-Si modules. In terms of production, the thin-film cells use a special technique to deposit a very thin layer of semiconductor materials on materials like glass, stainless steel or plastic. Thin-film modules do not use metals like silver or silicon and require less amount of metals overall than c-Si modules, but more glass in general (IEA, 2020). Reduction of material usage and increasing efficiency by embracing thinner films is the focus of the second generation (Ardente et al., 2016). The third-generation technologies focus on double, triple junction and nanotechnology to achieve high levels of efficiency at a reduced cost (Ardente et al., 2016). These are emerging novel technologies like organic PV, perovskite and tandem solar cells..

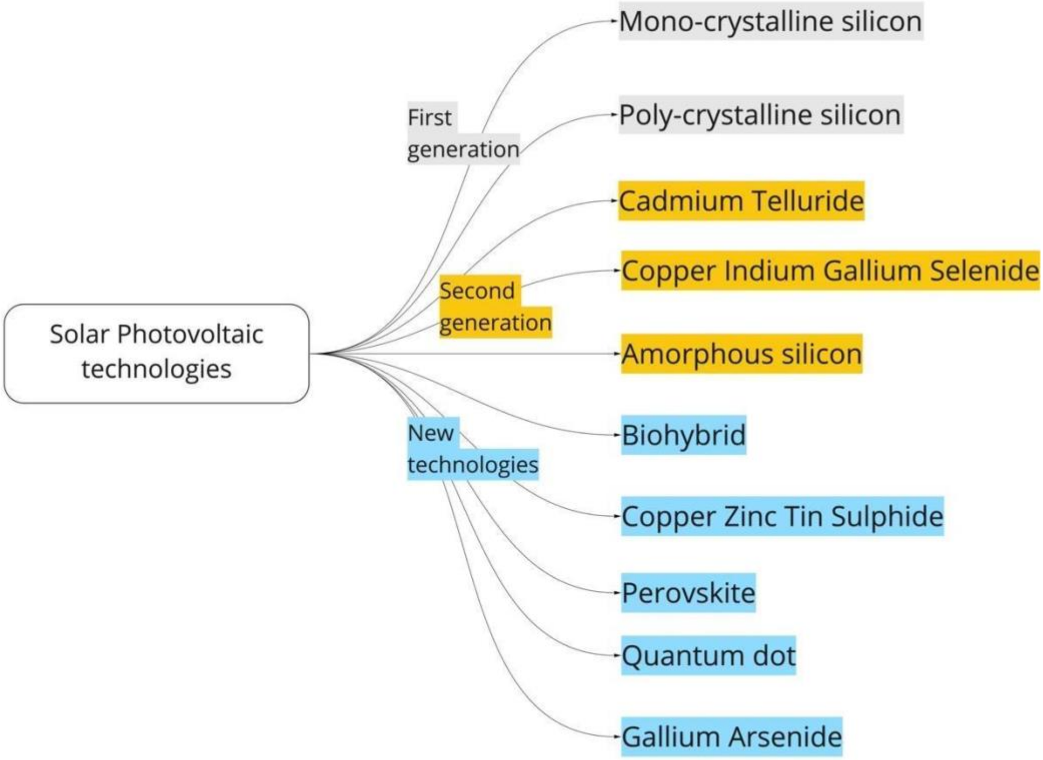

Figure 3. Different kind of PV technologies prominent in the market and developing in the lab scale; author's elaboration adapted from Ardente et al. (2016)

More than 90% of the PV modules present in the current market are thick-layer cells with crystalline silicon wafer technology (Buchholz and Brandenburg, 2018). In 2020, 95% of the global solar PV capacity addition came from installation of c-Si modules. Literature suggests that the thin-film and other novel technologies will attain a larger market share in future (Weckend, Wade and Heath, 2016). Alternative PV technologies are currently in the development phase but less mature for extensive market penetration in next three decades, such as copper zinc tin sulphide, perovskite, organic PV and colloidal quantum dot PV (Carrara *et al.*, 2020). These technologies are interesting for development because they show a higher rate of energy conversion efficiency. For example, the perovskite cells at the lab scale have displayed efficiency levels above 25% according to NREL (2019). However, there are issues in their practical implementation regarding their stability and the fact that they would need to be scaled up enormously to match the output of a commercial silicon based PV module.

Metals have played a central role in the development of several clean energy technologies which we use today. Using their material combination in alloys, the solar cells are able to bring superior functionalities (IEA, 2021). The Figure 4 adapted from Ardente et al. (2016) shows typical material composition of a crystalline silicon PV module. The report by Carrara et al. (2020) also provide a coherent overview of material demand for PV technologies. Glass is the predominant material used in silicon-based PV modules, which is essential to provide protection to the solar cells while being transparent so that most of the sunlight can enter the cells. In case of thin film modules, the percentage of glass material reaches to about 97% (Cucchiella et al., 2015). The frame is made of aluminium, which provides support to the module structure and copper is used for wiring. These two metals are also used for internal conductors. The EVA adhesive is used for the encapsulation layer and the back sheet layer is based on polyvinyl fluoride. The core of a PV module, solar cell, is made from a combination of silicon metal and other metals like silver, tin and lead in small quantities.

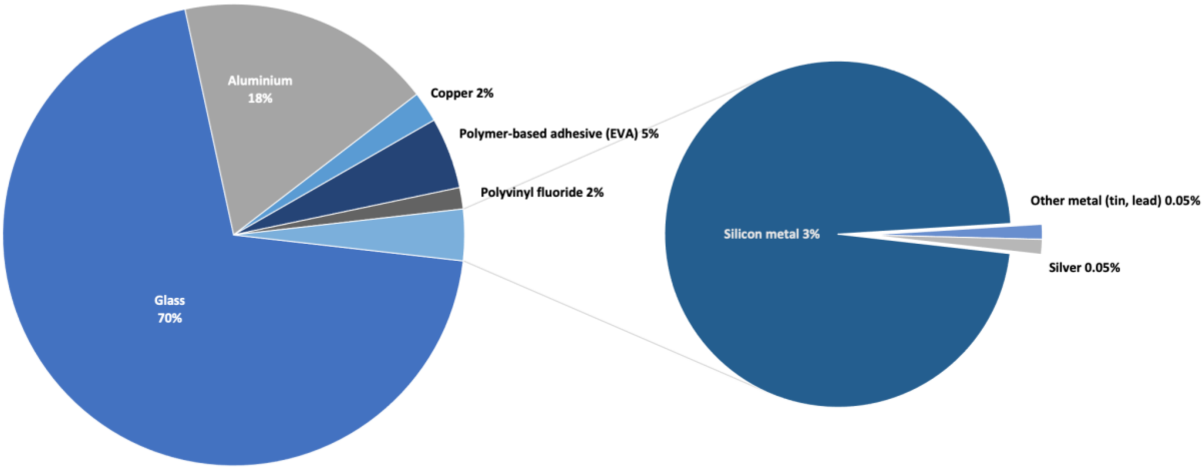

Figure 4. Material composition of c-Si PV module, adapted from Ardente et al. (2016)

As the transition to clean energy accelerates globally, the deployment of energy systems like solar photovoltaics on a growing scale will increase the material demand. The PV technologies mentioned earlier require materials for their production - general materials which are typical for the components of PV modules and specific materials for solar cells. The publication on critical minerals for energy transition reports that building solar photovoltaic plants generally demands more minerals than their counterparts running on fossil fuels (IEA, 2021). Figure 5 below encapsulates the major elements and their applications. Except concrete, glass and plastic, it can be noted that most of the raw materials are metals, of which many are sourced from outside of Europe. Companies producing PV modules using imported materials can become quickly affected in case of changes in regulations or instability in the supply chain. Such a potential for disruption was observed in the Covid-19 pandemic, and has created a larger source of concern for the overall industry. This has resulted in growing scrutiny also due to the high geographical concentration of material sourcing, processing and production of the PV systems (IEA, 2021).

The European Commission has shortlisted raw materials and marked them as critical for their close association with the EU economy and potential risks in their supply. The list is published every three years with the objective to strengthen the competitiveness of the European industry and to enhance priorities related to the circular economy and help negotiate the future trade agreements. The EU Critical Raw Materials (CRMs) list was first published in 2011, then subsequently in 2014, 2017 and 2020. Out of the 30 CRMs in the fourth list, the ones used in the solar PV supply chain are Indium, Gallium, and Silicon Metal (European Commission, 2020). Increasingly, the PV systems are integrated with energy storage for which Lithium is an essential element. The technological progress in the PV modules such as thin-film rely highly on the access to the growing number of raw materials. Buchholz and Brandenburg (2018) report an increase of 10-50% in the demand for these metals along with Selenium, Cadmium and Tellurium considering all of them being used in thin-film technologies.

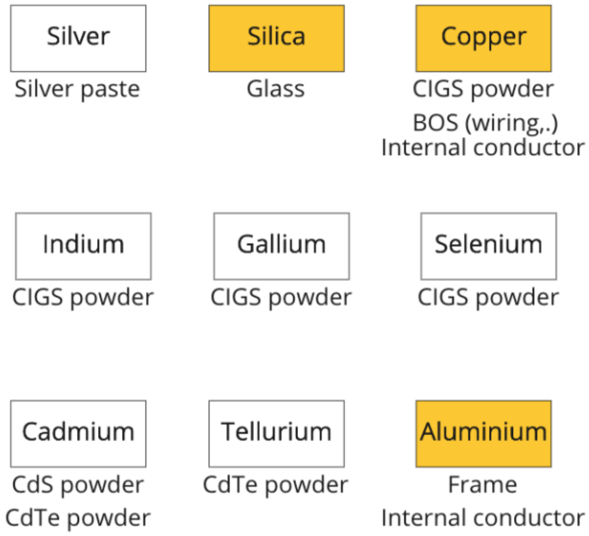

Figure 5. Metals essential for the future PV module production, highlighted metals are used in all kind of technologies; author's elaboration adapted from Carrara et al. (2020) and Cucchiella et al. (2015)

Contrary to the conventional energy sources like natural gas or oil, the supply chain for materials and production of clean energy technologies are more complex and in some cases, even less transparent (IEA, 2021). The future projections for material demand of a renewable energy technology like solar PV depend on the market share of related technologies with significant pressure on germanium, tellurium, indium and silicon demand in the EU as well as globally (Carrara *et al.*, 2020). The deployment of increasing solar capacity entails larger production and requirement of materials for components, most of which are metals. China produces the highest number of PV modules globally every year. Even before the production of modules, processing and refining raw materials was also highly concentrated in China. By contrast, if there is a shortage in the future for the essential raw materials described earlier, only the supply of new PV modules is affected. The owners using the existing PV modules are not affected. This is unlike fossil fuels where all the consumers and operators using natural gas or oil get affected with the changes in price or shortages (IEA, 2021).

2.2 PV deployment and its consequences

By 2040, the expansion of renewables in the EU's electricity production might account for two-thirds according to the International Energy Agency (IEA, 2020). The pragmatic vision from IEA's sustainable development scenario involves three topics for the evolution of energy sector along the Paris Agreement. These are saving energy on the demand side, improving energy efficiency, and replacing fossil fuels by renewable energy sources (IEA, 2020). PV technologies are being deployed faster than ever primarily because renewable energy sources are assigned a key role in achieving the energy transition goals. These goals are bolstered by several agreements to mitigate climate change, most notably the Paris Climate Agreement. The Figure 6 below shows capacity scenarios committed in Europe and globally up to 2050. The three situations HDS, MDS and LDS refer to the high, medium and low demand scenarios respectively, where MDS is considered as a baseline scenario (Carrara et al., 2020). From the graphs, it can be observed that the surge in PV capacity has started from around the year 2010 while the curve steeps upwards from 2020 for global scenario and 2030 for EU to achieve the HDS or MDS situation.

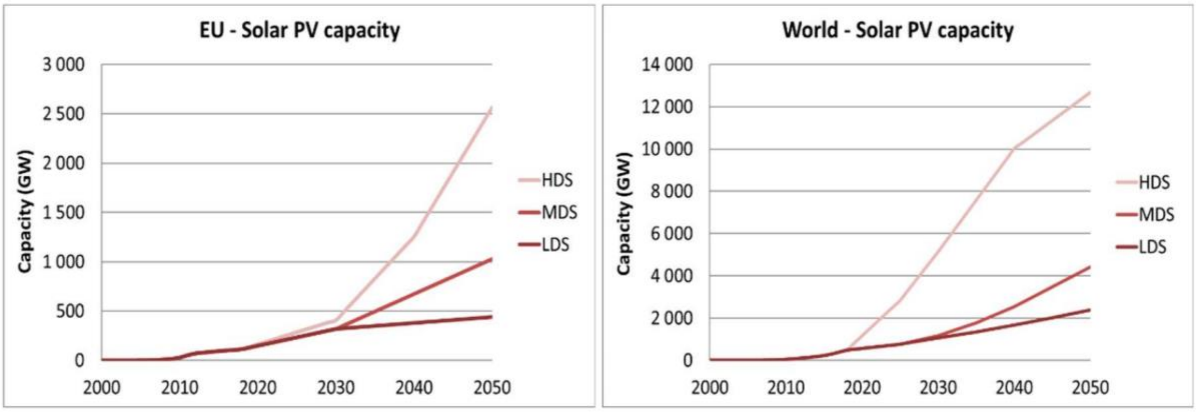

Figure 6. Solar PV capacity in EU and World over time with low, high and medium demand scenario, sourced from Carrara et al. (2020)

Although there are several technologies for low carbon energy generation like wind turbines, the solar PVs find sheer volume of capacity addition due to their ease of installation (IEA, 2021). PV technologies, along with wind power, are already competitive and cheaper in terms of energy generation costs (LCOE) than new utility scale coal and gas power plants, making them an even more attractive economic investment in the EU27 (European Commission, 2020). **Levelized cost of energy** (LCOE) is an indicator used to compare the net present costs of energy generated by a plant/technology over its lifetime. A unit of €/kWh is used to represent the LCOE of the energy generated.

The installation of PV systems are occurring majorly at three scales: residential, commercial and industrial, and utility. Both residential and commercial and industrial installations are used to cover their own electricity demands. The PV modules for residential and commercial sectors are generally installed at rooftops. The costs for energy generation for rooftop PV systems in the European countries dropped about 80% since 2008, driven by a rapid decline in the CAPEX costs (European Commission, 2020). The utility scale installations are operated to supply the electricity to the grid and are typically ground-mounted power plants (recently, also on water surface). In terms of the installation capacity, utility scale are typically larger in size compared with the others, and above 1 MW (IEA PVPS, n.d.). In terms of LCOE, the costs for utility scale installations in Europe ranged between € 43-168 per MWh in 2018 compared with € 70-188 per MWh for rooftop installations (European Commission, 2020). These differences can be explained by the amount of solar irradiation a country receives and the costs associated with the CAPEX depending on country to country (IRENA, 2019). Many politics also promote deployment of PV systems and renewable energy sources in general. To achieve the energy transition, many governments have introduced beneficial tax policies for investments in PV systems. The governments also utilise other economic mechanisms like feed-in tariffs to increase the overall adoption and investment in the PV systems at their level. A feed-in tariff provides a fixed price to the utility park operator for the energy they produce, usually for about 20 years.

The current trends in acceptance also exhibit positive growth for the solar industry with 130 countries supporting the PV technology in one form or another (IEA, 2020). A second increasing trend was reported in the installation of solar capacity between 2016 and 2020, after the one which went on increasing until 2011 (Solar Power Europe, 2020). There are many factors which were reported to explain the second boost for solar sector in the EU. Some of these are high demand for self-consumption, access to low-cost financing and attractive feed-in premiums for commercial installations (Sica et al., 2018) (Solar Power Europe, 2020). On the other hand, the economies of scale and rapid development of the technology can also be attributed for making the PV systems cost competitive, according to Renewables 2020 forecast by IEA (2020). Germany is the largest solar market both in terms of the total installation of 4.8 GW and 651 W per capita in 2020 (Solar Power Europe, 2020). In addition to the above mentioned drivers, the attractive auctioning for systems up to 10 MW and a proven regulatory scheme to guide the investment process played a key role to drive solar sector in Germany (Solar Power Europe, 2020). Netherlands follow similarly in terms of both total and per capita installation and has shown increased interest in multifunctional use of space, for example carports and floating solar. According to Solar Power Europe (2020), the main driver particular for the Netherlands was net metering for residential and small businesses. Countries like Spain, Poland and France follow in terms of total installation till 2020 (Solar Power Europe, 2020).

There are five major consequences reported in this section from the deployment of PV systems. These are related to (i) energy security of country/region, (ii) supply-demand mismatch, (iii) environmental impacts during the lifecycle, (iv) creation of a material dependency and (v) waste generation at EoL.

Securing the supply of energy is an important agenda in the EU and globally, and has promoted renewable energy sources like solar energy (Nilsson et al., 2009). It is likely that harnessing solar energy can relax the energy dependence of countries in the current situation and end today's geopolitics around the fossil fuels (Hache, 2018). The impact assessment on EU Energy Roadmap for 2050 suggest energy security as one of the three overarching policy objectives (Jonsson et al., 2015). The transition is also favoured in terms of macroeconomics. Contrary to the PV systems, the costs for fossil-based power plants strongly depend on the cost of fuels (IEA, 2021). The restrictive rules on pollutant emissions which countries in the EU are pushing forward is also one of the reason likely affecting the cost of electricity generated by these power plants. In the EU, increasing trends in LCOE estimates for technologies like gas-fired power plants, supercritical coal-fired power plants and combine heat and power (CHP) were observed between 2008 and 2018 (European Commission, 2020).

Renewable sources of energy such as wind and solar are intermittent in nature, meaning they are available only in certain time periods. For solar, this means that there is a peak in availability of the generated energy during the day and no energy is generated after sunset. To offset the deviations between the actual generation and the forecasted generation, some form of energy reserve must be held and operated (Pescia & Redl, 2015). The inherent dependence of energy generation on weather makes the integration into the electric power grid challenging due to variability and lack of predictability (Bird et al., 2016). There might be cases when more energy is generated than required, which might overwhelm the electric grid. In these cases, either the grid can be improved or a curtailment is required, referring to the use of less power than potentially available at the given time (Bird et al., 2016). Both of these options require additional costs, which are reported to be 5 € per MWh for rooftop PV installations and around 8.5 € per MWh for ground mounted installations (Pescia & Redl, 2015). The studies on renewable energy technologies report that curtailment levels are likely to grow with higher penetration of solar and wind energy generation (Bird et al., 2016).

Following the large-scale deployment around the world, there have always been concerns about the environmental impacts of solar PV. Figure 7 depicts the comparison of CO_2 emissions between different energy generating technologies. Given that emissions from PV systems are significantly lower than fossil-based power plants, they seem to make a better choice to fit in the sustainable energy mix. However, it is important to understand the reasons behind the existing emissions.

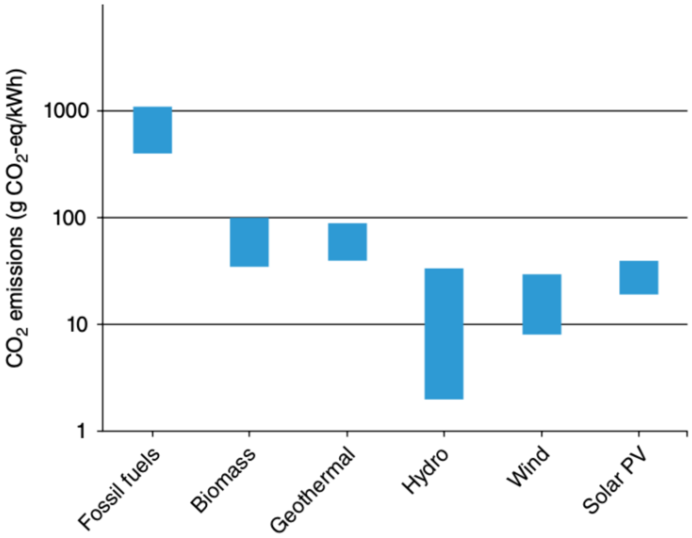

Figure 7. Comparison of greenhouse gases emission in CO$_2$ equivalents for different energy sources. Sourced from Reinders et al. (2016)

Several studies have proven that the production stage is primarily responsible for the most global warming potential impacts (de Wild – Scholten et al., 2008) (Gerbinet et al., 2014). The mining of raw materials and processing of materials amount to two-thirds of the GHGs emissions. The GHGs emissions, or climate impacts, for the EoL phase contributes between 5-20% of the overall emissions. The climate impacts from the operational stage when the PV systems are used can be considered negligible in comparison (Gerbinet et al., 2014) but activities like maintenance and replacement can increase the emissions. These impacts also depend on the setting of PV deployment such as the geographical location, solar irradiance, scale of installation, type of panels and the associated components (Gerbinet et al., 2014). For example, the centralised projects would likely have less climate impacts per unit power as they require less transportation than decentralised installations of the similar characteristics (Stolz et al., 2016). The climate impacts from the PV supply chain calculated with LCA are reported in Figure 8 below adapted from (NREL, 2012) (Fthenakis, 2000). The supply chain is divided into upstream, operation and downstream parts. The black boxes indicate potential interventions to create a second life use or recover materials.

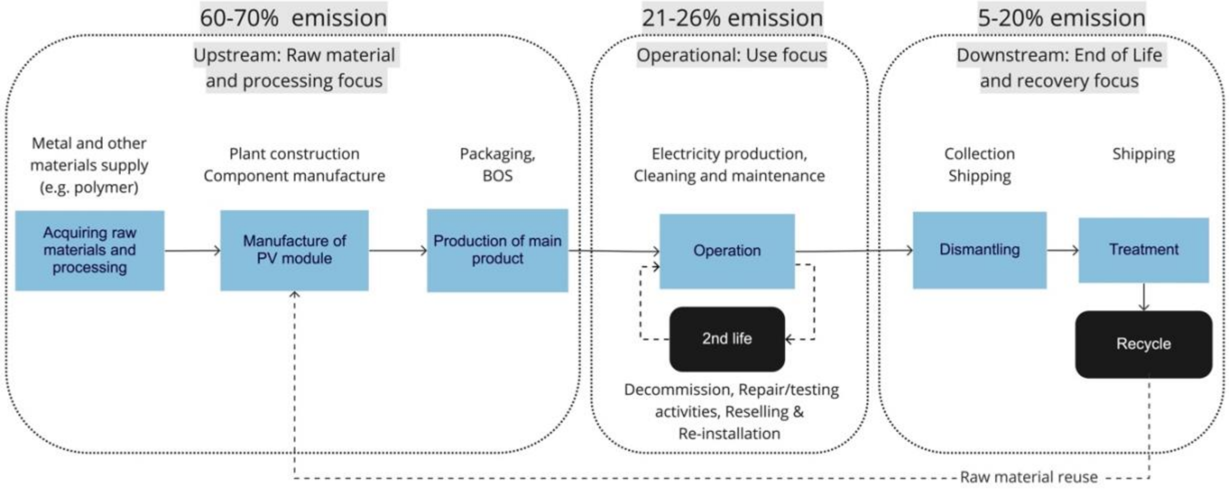

Figure 8. Climate change impact studied over the entire PV supply chain, adapted from NREL (2012) and Fthenakis (2000)

Since the LCA studies mostly report energy payback time or climate impacts, it is important to take note of possible impacts transfers (Gerbinet et al., 2014). It is likely that the pace of change in the energy sector puts more burden on material dependencies. The energy systems producing clean energy differ significantly from the ones using fossil fuels in terms of material usage. On one hand, the power plant running on PV modules does not use any fuel during operations but requires large amounts of materials for its construction. Generally, the amount of materials used for construction of a PV plant is larger compared with requirements for the infrastructure of its fossil fuel counterpart (IEA, 2021). A major issue in the EU is the supply of these materials. The mining activity of raw materials essential for clean energy technologies is limited in the EU and the major suppliers are located in a few limited geographies (Carrara et al., 2020). Securing the raw materials to transition to cleaner energy and achieving energy security is a crucial agenda for the EU (European Commission, 2020). This implies that the transition to clean energy is closely associated with the demand for critical raw materials not just in the EU but globally.

Another concerning consequence of a large-scale deployment of PV modules is the generation of amounts of waste as soon as they reach their EoL. Future projections illustrate large streams of PV module waste. The Figure 9 below illustrates the amount of PV waste accumulating until 2050 while assuming a 30-year technical lifetime, based two scenarios assumptions (Weckend et al., 2016). The first scenario is regular, and the second is early loss, which assumes that a proportion of PV modules will suffer early life failures (Weckend et al., 2016). These early life failures lower the lifetime of PV modules, and one of the reason is installation and transportation damages. The drastic increase in the cumulative waste can be observed for both scenarios, expecting between 60-78 million tons by 2050. The two scenarios account for different uncertainties arising from the limited availability of data (Weckend et al., 2016). The early-loss scenario is based on the assumptions for the early PV failures and losses.

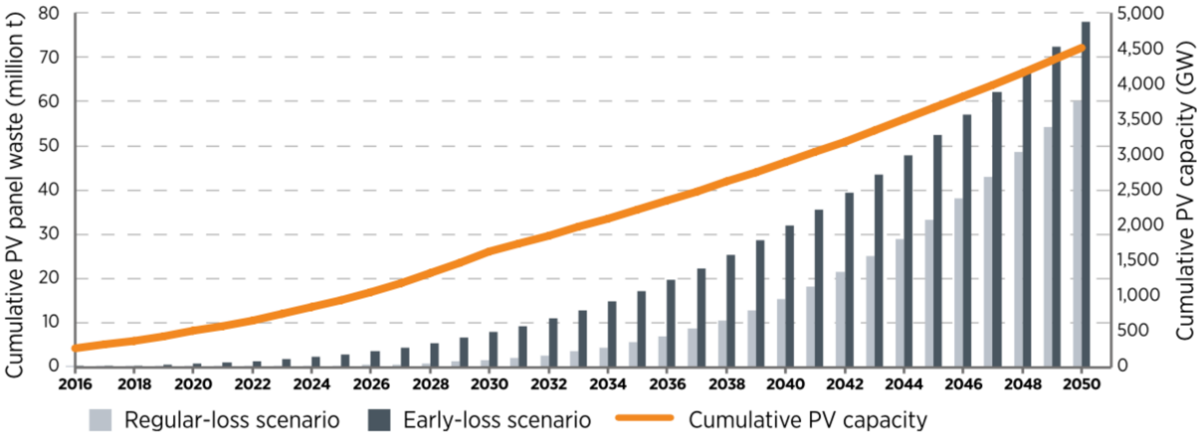

Figure 9. Time series projections of global cumulative PV waste for two scenarios and global cumulative PV capacity. Sourced from Weckend et al. (2016)

The waste volume estimations for PV modules can be approached by modelling with global PV growth rate as one of the primary inputs. However, there are other nuances which need to be accounted for as these affect the projections. For example, technological advancements make modules more powerful and lighter resulting in lower weight-to-power ratio. The weight reductions come from optimised design of the module incorporating material savings, thinner layers and frames. The assumption in the IEA study by Weckend et al. (2016) indicates that the weight-to-power ratio will be almost halved between 2010 and 2050. Hence, the advancements are driving towards reduction in material use per unit of power generated (Marini *et al.*, 2014) (McDonald and Pearce, 2010).

2.3 End-of-Life of PV modules

Majority of the PV installations around the world still operate and would only become waste after the end of their lifetime. Visually, it is illustrated in Figure 9 as the gap separating the cumulative capacity and waste amount. For example, the majority of the PV modules installed in the year 2020 would show up in the EoL not before 2045 in a general scenario. Due to such a long operational period of the PV modules, the task of estimating plant lifetimes becomes challenging (Weckend et al., 2016). In order to understand the waste generation and its complexities, it becomes important to discuss the magnitudes of lifetime and different treatment routes at the EoL. In this section, the important concept of service and technical lifetimes are explained in the context of PV modules, followed by describing different treatment routes which are observed when the PV modules reach their EoL.

Service lifetime refers to the time period when a product is in use (Murakami et al., 2010), while technical lifetime is an indicator of the maximum period a product can function physically at acceptable performance rates (Burns & Cooper, 2010). These are important definitions for a product and are increasingly becoming prominent in the discussions about sustainable management of resource stock (PLATE, 2021). For the case of PV modules, they are usually in operation for 20-30 years and slowly degrade in terms of electricity generation efficiency over time. Hence, a central value of 25 years is generally assumed to be their lifetime even if some can last more than 30 years. Studies performing life cycle impact analysis use an assumption of 30 years as recommended by the IEA-PVPS (Frischknecht *et al.*, 2016) (de Wild – Scholten et al., 2008). The electricity generated from PV modules change over their lifetime primarily because of field degradation. The rate of degradation is exponential but can be roughly considered to be linear due to low degradation level. In practice, an average rate of 0.7% per year is assumed (Frischknecht et al., 2016) and has been reported for the PV modules but new technologies are expected to reduce it to 0.5% per year (Strevel *et al.*, 2016).

PV modules are replaced with more efficient ones after they reach the end of service lifetime, which does not necessarily mean they have reached their technical lifetime. The failures and wear-outs in early and mid-life of PV often turn them into waste stream before reaching their EoL targets. Based on user complaints, the primary failures are due to optical issues, power loss, electrical systems and glass breakages (IEA, 2014). Hence, there are instances where healthy PV modules get discarded before they reach their technical lifetime. The three most common reasons reported are revamping, repowering and due to insurance claims when the installation suffer damage (Tsanakas et al., 2019). These include different levels of adjustments to the power plant with an overall objective to either achieve higher performance of the existing asset or to restore it to the original situation. The effortless opportunity to improve output of the existing power plants with high feed-in tariffs becomes complicated when specific regulations are introduced (Zoco, 2018). Given the sharp decline in the costs of PV systems, an improvement in performance can result in an overall increased internal rate of return on the original investment (Zoco, 2018). However, each intervention requires a case-by-case analysis to understand the opportunity depending on factors like return on investment, local regulations, warranty coverage and technical aspects (Zoco, 2018).

Revamping involves the replacement of components which suffer degradation, defect and lower performance than originally intended. These are not covered by warranty and are therefore replaced with better functioning components which do not change the fixed power of the system (Zoco, 2018). In the field, revamping can mean that the PV system or its individual components are partially replaced, removed, retrofitted or reinstalled in the same or different configuration (Zoco, 2018). On the other hand, repowering is used to extend the life of PV plants with the objective to increase power rating of the system. During repowering, the increment in the power rating is organised within the existing surface boundaries of the power plant. Generally after about 20 to 25 years, the park operators decide to repower (Zoco, 2018). Often, the events like earthquake, fire, storm, vandalism and so on can lead to damage the system. In these cases, the defunct modules and components like inverter are claimed within the warranty are replaced or repaired if possible (Zoco, 2018).

From a global perspective, the PV industry's waste is still considered general waste, with the EU as an exception. In the EU, PV waste is counted and approached as e-waste according to the WEEE Directive (European Parliament, 2012). WEEE Directive is a regulatory framework to address waste streams from Electrical and Electronics Equipment (EEE). There are other different approaches to waste management in different countries where the responsibility depends on society, consumers and/or producers. This report focuses on the practice in the EU where producers are held responsible for managing the waste based on the principle of Extended Producer Responsibility (EPR). In EPR strategy, a producer is held liable for a product after its post-consumer stage, hence adding up all the costs for managing the waste (Atasu and Subramanian, 2012). Since EPR has been implemented in the form of legislation for e-waste in the EU, the fate of PV waste is up to the hands of producers (European Parliament, 2012).

Similar to the disposal methods for an electronic product, there are three major routes for dealing with the PV modules after decommissioning: landfilling, recycling and reusing (Weckend et al., 2016). Landfilling after incineration is also considered as an option. There a several factors influencing the economics of the treatment pathways. Some of these are type of treatment method, transportation and regulations. At times, some of the larger components of PV modules like the glass panels, metal frame and the wires are separated and recycled (or reused) separately.

Landfilling is a disposal method in which the waste is dumped into the ground. The ground is dug up and contained in specialised impermeable layers to contain the waste constituents from leaking in the ground, technically known as leaching. Landfills require large land areas and have a finite space for storage. In addition, the waste dumped in these landfills can be considered as materials lost from the system. The introduction of electronic equipment in the waste stream, including the PV modules is a direct loss of valuable resource stock (Faircloth et al., 2019). Since the economics of recycling are not profitable as of today, is it often reported that electronic waste is shipped to countries where the environmental laws are very liberal (Weckend et al., 2016). The legislation in the EU has referenced measures to prevent illegal shipments for PV modules (European Parliament and Council, 2006).

PV modules disposed in landfills without treatment are likely to cause negative effects on environment and human health due to leaching of harmful chemicals and causing burden of conventional resources (Stolz et al., 2016). Sinha et al. (2020) reports their finding on the potential health impacts of landfilling the PV modules. The most abundant materials in a PV module are glass, polymer, copper and aluminium, which do not pose health risks to humans (Sinha et al., 2020). Other constituents like silicon, lead, cadmium, selenium and alloys used in the semiconductors can be potentially hazardous for the human health and environment

(Sinha et al., 2020). Overall, it was found in their study that even with the many protective assumptions for health risk, the landfilling did not represent risk of cancer or non-cancer outcomes based on the thresholds set by World Health Organization (WHO) and U.S. Environmental Protection Agency (EPA) (Sinha et al., 2020). However, the researchers and the larger scientific community have recognised the fact that landfill is an unsustainable way of waste disposal (Sinha et al., 2020), which has resulted in this activity being prohibited in several countries with either legislation or economic mechanisms. In the EU, the landfill directive (European Commission, 1999) provides the guidelines to strict operational requirements of the landfill sites and limit the share of waste disposal to it.

Given the restrictions to landfilling in the EU countries, recycling has developed as the preferred option. The aim of recycling is to separate the components to be re-used or recycled as raw materials in different activities. Figure 10 and Figure 11 illustrate the generic recycling process for c-Si and thin-film PV modules. The study by Faircloth et al. (2019) reports that recycling of dominant c-Si technology PV modules is less environmentally burdening compared to the landfilling alternative given that the analysis is conducted from cradle-to-cradle. Unlike landfilling where all the material resource is lost, the recycling process receives credits for avoiding the impacts associated with production of new materials (Faircloth et al., 2019) (Vellini et al., 2017).

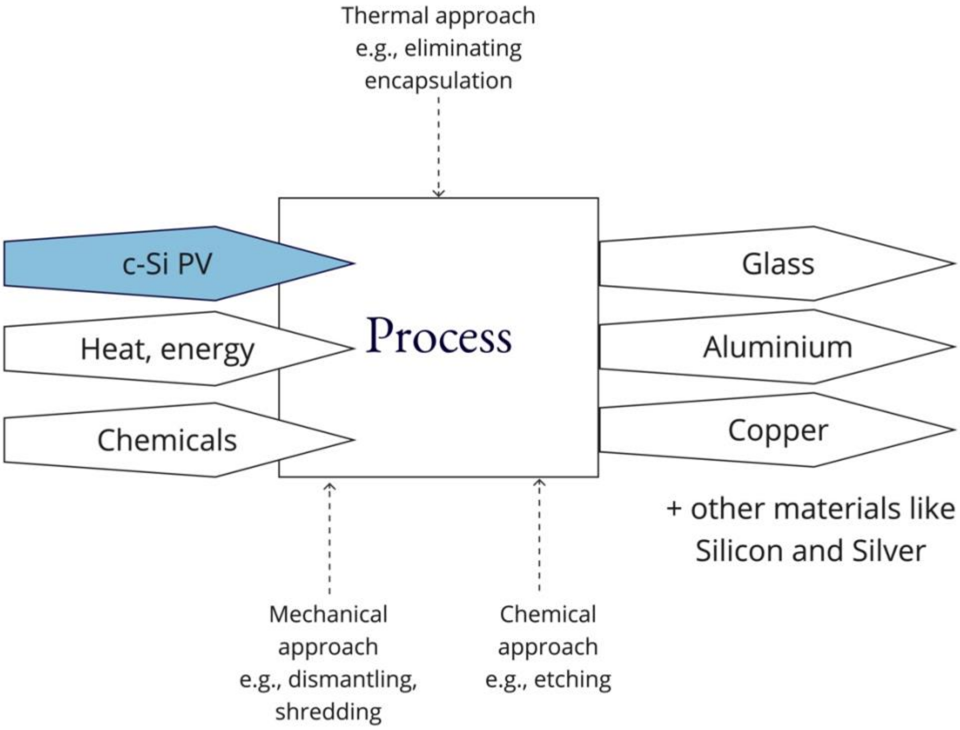

Figure 10. Simplified schematic describing recycling process for crystalline silicon PV module, adapted from Fthenakis (2000) and Sica et al. (2018)

The recycling process is energy intensive and the process requires chemical methods to remove the impurities from the recovered materials (Sander *et al.*, 2007). If the impurities are not removed, it can result in lowering the selling prices of the material in market (Ardente *et al.*, 2016). The initial separation process for PV modules follow fairly similar routes for both silicon based and thin film modules, however, different separation techniques are used in the following steps due to different material composition (Sica et al., 2018). Figure 11 shows simplified recycling process the CdTe thin film module, adapted from First Solar (Sica et al., 2018) (Fthenakis, 2000).

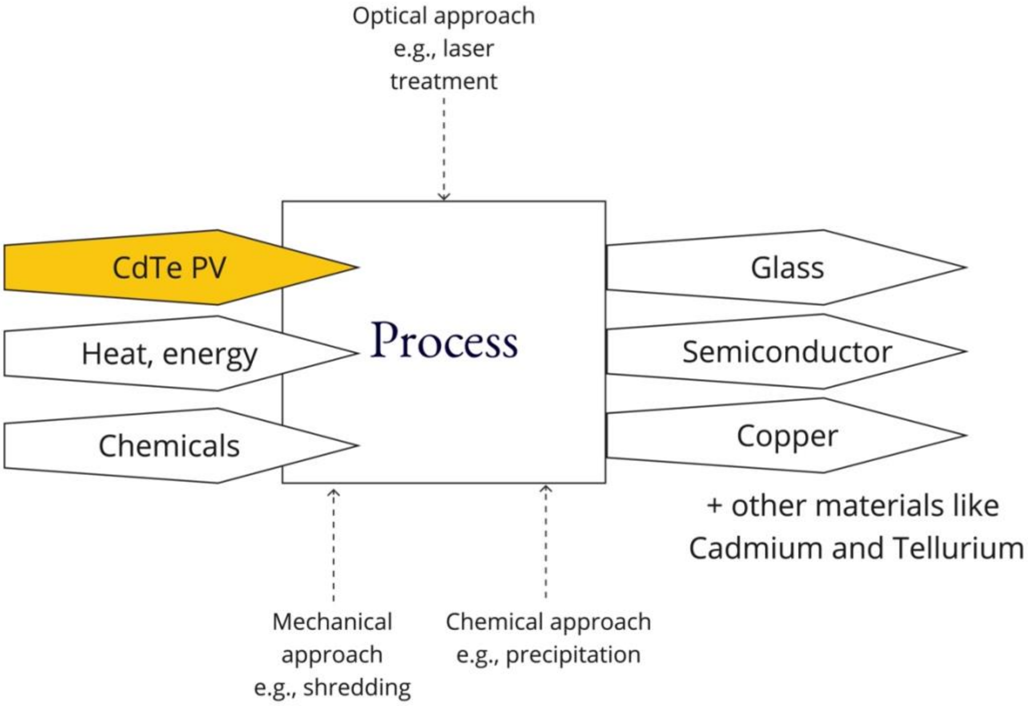

Figure 11. Simplified schematic describing recycling process for thin film PV module, adapted from Fthenakis (2000) and Sica et al. (2018)

Economic feasibility of the recycling process is determined by the value of input requirements such as capital expenditure for process units, energy requirements, transport to the facility and the output generated from the process such as raw materials. The increased recovery rates for materials such as glass over the past years is recognised by (Komoto et al., 2018) as an economic enabler. Currently, an extra fee is also collected to process the waste PV modules. Either the recycling takes place at the manufacturing facilities, or handled by the specialised facilities. Most of the manufacturers become members of collective waste management organisations such as PV Cycle and Deutsche Solar. These organisations provide waste handling and compliance services for their members (PV Cycle, 2019).

2.4 Circular economy and its strategies

Circular economy is a systemic approach, different to the currently dominant “take-make-waste” linear economy model. As the name suggests, the material (and energy) flow is circular and the “loops" are closed in the circular economy. Given the high growth in the global middle class, the linear economy model is reaching environmental limits (Bakker and Schuit, 2017). There are limits to linear consumption entailing significant resource losses. The circular economy model promises to resolve the sustainability challenges which the linear model fails to attain for the future, benefiting both the businesses and the environment. The report by the Ellen MacArthur Foundation with McKinsey (2013) refer to it as an industrial economy that is restorative, relies on renewable energy and eliminates toxic chemical and waste. In a way, this model aims to decouple economic revenues from material consumption (Ellen MacArthur Foundation, 2013). For example, circular material usage seeks to lower the generation of waste and imports of raw materials (De Schoenmakere and Gillabel, 2017).

The Ellen MacArthur Foundation, a non-governmental organisation in the UK has significantly contributed to the conceptual development of circular economy (Kirchherr et al., 2017). They list three principles on which the circular economy is based: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (Ellen MacArthur Foundation, 2020). The first principle aims to integrate the negative externalities within the process. For example, optimising the streams in industrial process to utilise waste streams from one process as raw material input for another process, such as industrial symbiosis. It also involves using materials which wouldn't cause hazard in the future, like using the green chemistry approach. The objective of the second principle is to keep the products and materials in use for longer. Extending lifetime of a product and changing the ownership model to performance-based instead of product-based are ways to fulfil the purpose of the second principle. The third principle suggests to enrich natural systems and is related to the wellbeing of the biosphere such as soil and also to avoid fossil-based consumption. The butterfly diagram by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, n.d.) well illustrates these principles and the relationship between biological renewable cycle and the technical stock management.

Building on works of Stahel (1982), Bocken et al. (2016) introduces three basic premises of circular economy - closing material loops, slowing material loops and narrowing material loops. Closing the loop refers to recycling of postconsumer waste, slowing the loop refers to retaining the product value for as long as possible and narrowing the loop directs to improving the efficiency. Following the premises from Bocken et al. (2016) and the second principle of circular economy, Potting *et al.,* (2017) have listed nine circular strategies to keep the products and materials in use for as long as possible. These circular strategies can be effectively used as a guideline to achieve circularity within the production chain, as seen in Figure 12 below. These strategies are listed in the order of circularity potential based on the fundamental principles of circular economy. Increasing circularity also results in higher demand of innovation in the technology, product design and revenue model (Potting et al., 2017). For industries which are already implementing one of these goals, even moving up the ladder represents a shift towards a more circular business practice.

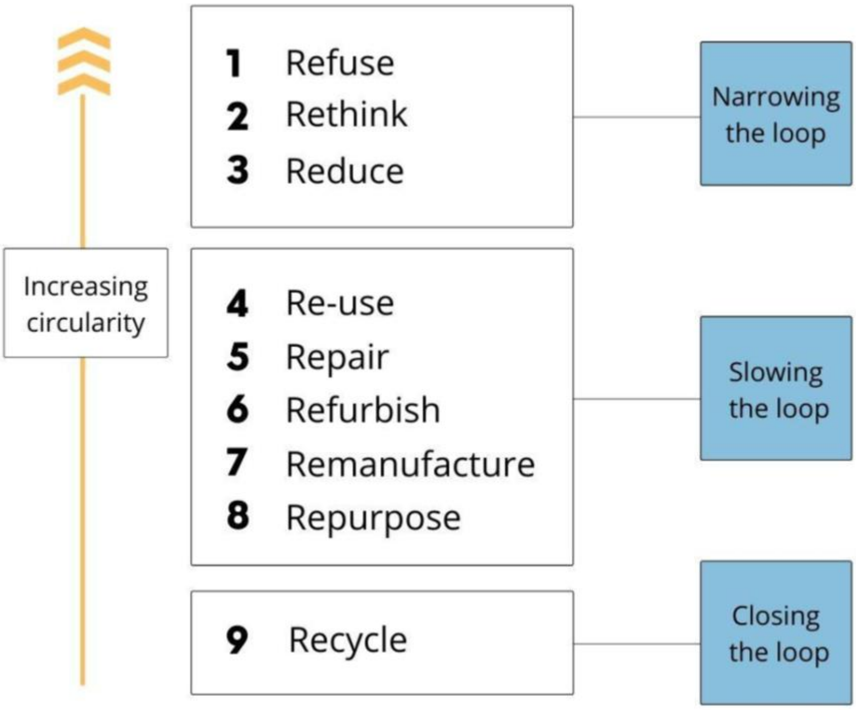

Figure 12. 9R framework for depicting circular strategies in a production chain, adapted from Potting et al. (2017) and Bocken et al. (2016)

The first three circular strategies by Potting et al. (2017) are collectively referred to smarter product use and manufacturing. "Refuse" implies that a product can be become redundant if its function is met by another radically different product with a better performance and environmental specifications. When the product is used more intensively, such as by sharing, it implies "rethink" strategy. Rethinking the business models to match circular goals is becoming prominent in the market. The third strategy "reduce" refer to increasing the efficiency in terms of manufacturing by reducing the material and energy consumption of the processes. In terminology of Bocken et al. (2016), these circular strategies are implied to narrow the loop.

For the next group of strategies, the aim is to keep products, components and materials in the economy at the highest value possible, for as long as possible (Bakker and Schuit, 2017). Potting et al. (2017) refer to them collectively as the circular strategies which extend lifespan of product and their components. The products can simply be used for a longer period, or their lives can be extended by proper servicing and maintenance, or even by repair or refurbishment (Potting et al., 2017). By "reuse" of a discarded product, a consumer can still fulfil their functional requirements. If the products show defect, they can be "repaired" and maintained to serve their original function. Old products can be restored for the original function and brought up to date by "refurbishing" and if new parts are required then it is called "remanufacturing". Although maintenance of product to keep their performance at optimal level is omnipresent, Parker et al., (2015) suggest that remanufacturing is still undervalued in the industrial setting. Turning the discarded products into a new one with different functionality implies "repurposing". In terminology of Bocken et al. (2016), these circular strategies are implied to slow the loop. Product-service system business models show these strategies. Bocken et al., (2017) report that the busines models associated with these strategies appear low on the corporate agenda. These form the basis of this study on second life photovoltaics.

The final strategy aims to provide useful application of the materials contained in the product (Potting et al., 2017). By “recycling”, the material resources discarded as waste are transformed into a form which is more valuable in the market. It is one of the most evident circular strategy in the industrial landscape (Bocken et al., 2017). Often, the transformed material close the loop by turning into secondary raw material for the original application or a different purpose. It is also possible that the seemingly waste material for one industry can play the role of raw material input for another industry. When industries identify and agree for exchanging these material streams, the model creates value by closing the loop and is popularly known as industrial symbiosis (Chertow, 2000).

2.5 Circular economy in the PV supply chain

After the material and energy use requirements in production, most concerns around PV modules revolve around how their waste is treated after decommissioning. According to the literature, Europe represents the second largest PV waste market globally, anticipating significant waste streams from Germany, Italy and France (Weckend et al., 2016). Since the regulations for the waste and PV sector are relatively developed in the EU, there exist both challenges and opportunities as the inflow of the PV waste stream increase. Given the material related issues in the supply chain, the previously discussed circular strategies should also be applied to the PV industry. The interest in a circular economy is ever-increasing (Merli et al., 2018), and applying the same principles to the PV industry can potentially help assess and achieve circularity. There are multiple ways to create value using interventions in the design phase, material choice, operations and material recovery. In this section, firstly, the benefits obtained from the innovations in the design phase are introduced. This is followed by discussing the possibility of extending the lifetime of the modules, which also forms the rationale behind the purpose of this study.

Since the production of PV modules is responsible for the majority of the GHGs emissions in the overall supply chain, material reduction through design and innovation must be implemented (Allwood et al., 2011). The “reduce” strategy or “narrowing the loop” can be interpreted as material efficiency in PV production since reducing material use is a highly desirable trait. Improving the resource efficiency in the design and production of PV modules goes along with the sustainable development goals. A reduction in material intensity and possible material substitution is possible using technology innovation. According to the analysis by Nassar, Wilburn and Goonan (2016), the material intensities for different solar cell materials show a declining trend due to advancements in the energy conversion efficiency and production process of the modules. Over the past decade, a decrease of 40-50% was observed in the use of silicon and silver for the manufacturing of solar cells. As reported in a report by the JRC (2018), the declining trend in silicon consumption is likely to reach a drop from 16 g/W in 2004 to 3 g/W in 2028. Since both silicon and silver are among the most expensive solar cells, it is important to explore alternative technologies that can substitute these materials. These innovations can reduce the costs further and unlock the deployment of PV technologies significantly. IEA (2021) lists CdTe, perovskite and GaAs modules to be further explored as alternative technology evolution pathways for harnessing solar energy.

Although new alloys and materials bring superior results, they often result in more energy-intensive recycling pathways. With more complexities in the product design and the material usage in the technology, recycling has become complicated. These technical complexities can also make repairing highly labour intensive and financially unattractive (Ellen MacArthur Foundation, 2016). There are some considerations to improve the results of material recovery from recycling. Design for recycling (DfR) is one of them, where importance is given to creating recycling-friendly panel designs. According to the literature and popular perspective, the strategy for recycling starts already at the design phase of the PV module (Gómez and Clyncke, 2011). The most important factor considered is an easier dismantling of the modules to avoid further damages, material losses and save time. The physical collection is also a critical element to achieve the high rates of recycling. It can be developed as the knowledge of regional stocks increases. It is also crucial for the recycling operators to consider the available stock and anticipated stock changes of the EoL PV modules in the market. Recovering materials from recycling of the PV modules have gained attention, but approaches to extend the lifespan are very limited.

Keeping the product and its components in service results in higher levels of circularity compared to the recovery of materials. Extending the lifetime of PV modules can be implemented using reuse, repair, refurbish, remanufacture and repurpose strategies, as discussed earlier by Potting et al. (2017). These strategies can keep the PV modules at their highest value in the economy for as long as possible, creating long-term value using regular inspection and maintenance of the system. Integration of the circular economy strategies in the business models can also enable companies to maintain their PV system for longer and harness most of its value. Since energy providers are in the best position to maintain their inventory, new business models are emerging to explore this opportunity (IRENA, 2020). Business models like energy-as-a-service (EaaS) allow companies to keep the ownership of the assets and provide energy-related services rather than supplying only energy to their customers. A study by IRENA (2020) on EaaS report that these models support the deployment of distributed energy generation such as PV systems and allow better management of the demand-side. Reusing is possible for the PVs, which are decommissioned earlier than their technical EoL, or in simple words, PVs, which can still largely convert sunlight into energy.

The European Commission (2019) also associates circular economy with reducing the burden in terms of environmental impacts while benefiting the economy. Giving a second life to the PV modules avoids further mining of natural resources to produce new modules and the energy used to treat waste. Allwood et al. (2011) suggest the supply chain actors can achieve new revenue streams by developing a second-hand supply chain. Mobilising these strategies can enable various opportunities for value creation using PV modules decommissioned before reaching their technical EoL. It can also create jobs in the repair sector, preserving the value embedded in the product while saving expenses on replacement (Bakker and Schuit, 2017). These business models can be applied mainly for the PV systems which suffer early losses, according to the study by Weckend et al. (2016). When the defects are identified at the initial phase, these modules are returned to the producer or service partner for quality diagnosis and repair potential to recover value. If there is visible economic feasibility for reselling, the repairing route is followed if required, but the selling price is reduced to approximately 70% of the original price (Weckend et al., 2016). Currently, the opportunities to prepare PV modules for second life require modules to be diagnosed, cleaned and repaired before being sent to the warehouse for selling. This study is focused on identifying such activities and mapping them to provide a better overview of the supply chain. If the modules are not compatible for a second life, recycling is the next preferred option (Weckend et al., 2016).

One of the oldest examples of PV reuse comes from a solar park built in the 1980s near Hesperia, California, installed for small domestic applications. However, the existing research has majorly focused on recycling and material recovery from PV modules. The work on the second life market has been relatively limited in the context of a circular economy. For example, the study by (Sica *et al.*, 2018) about the management of PV modules towards circular economy finds no mention of repairing or refurbishing. A study by CIRCUSOL partners reports that about 45-65% of the PV waste modules can be given a second life by repairing or refurbishing instead of directly joining the waste stream (CIRCUSOL, 2018). Hence, the lack of information about repairing plays the role of a barrier to extending the lifespan of products (Ellen MacArthur Foundation, 2016). In the case of PV, a study by Tsanakas *et al.* (2020) concluded with two central “pillars” to be addressed to enable a successful second life PV business case. One of them mentioned a gap in R&D existing because of the very limited literature on the amount of PV waste that needs to be addressed. Access to this information and the technical specifications could direct the analysis further in terms of visualising time evolutions, market projections, and estimated cost for repairing and bringing PV modules to a second life market. In this study, the research gap in developing successful deployment of second life PV modules is addressed by mapping the supply chain.

3. Methodology

This chapter outlines the design of the research. Furthermore, methodologies to realise the research objectives, including research methods, data collection and analysis methods, are discussed. Finally, the chapter presents the limitations of the choice of methodology.

3.1 Conception of the research

As the idea of second life PV modules is relatively novel, much of this study takes an exploratory approach to investigate the research questions. The activities relating to the second life solar PV modules can also differ depending on their past usage and future application. Furthermore, giving a second life is only one of the many concurrent efforts for achieving resource efficiency in the transition to a low-carbon future. Hence, it is critical to understand the potential and positioning of activities related to the second life PV modules. Moreover, the results of initial quantitative models conducted at the nascent stage of operation are bound to vary considerably unless a body of rich scholarship on the subject is available. Qualitative research can be valuable to gather nuanced information that models might not be able to comprehend. In this study, the main objective to explore the dynamics in the supply chain and filling the existing knowledge gaps that can inform policymaking for the PV industry by providing a comprehensive insight into the possible future states of PV modules currently in operation. Moreover, the CIRCUSOL project played an important role in conducting this research by providing direct supervision and knowledge resource from experts involved in the project.

3.2 Data collection methods

The data collected to answer the research questions came from both primary and secondary sources. The data collection efforts mainly involved review of peer-reviewed literature, “grey” literature and ten one-to-one interviews executed via *zoom* communication technology. The literature was reviewed at various points throughout the study to understand concepts related to solar energy sector, circular economy and specific information related to the European context. The sources were identified through a variety of academic databases including Google Scholar and ScienceDirect. Additionally, the publications from authorities such as European Commission, IEA (PVPS), IRENA and circular economy focused organisations like the Ellen MacArthur Foundation were consulted. However, due to the limited reporting of scholarship for second life PV supply chains, the most valuable information were gathered from the interviews.

For gathering the primary data, semi-structured interviews were chosen. The rationale for the interviews was to gather insufficiently understood knowledge on the interactions between the different industry actors in the supply chain of second life PV modules. The interviewees represented experts in the PV supply chain representing an installer, producer, producer responsibility agency, waste management company, second-hand reseller, repurpose company, recycler and researchers from academia. The intention of the interviews was to identify the underlying drivers which lead to the supply chain as it has come about in order to formulate and reconstruct the mapping with three different flows. The interviews were organised in the form of video call with duration between 1-2 hours because of pandemic conditions and presence of interviewees in different regions. The interview notes were used to record the important points. Full interview reports can be provided on request with full confidentiality.

The following table lists the name of interviewees and describes their role within the PV supply chain (or from a research perspective). The additional information about the experts and their relevance for the thesis work is attached in the Appendix B: List of interviewee details. Out of 12 experts who were contacted for interviews, only eight who responded were interviewed. Majority of these interviewees, 6 out of 8, are a part of the CIRCUSOL consortium. Hence, it took less time than usual to organise a meeting with them. Their participation in the project also implies that they are familiar with the idea of circular economy and second life applications of PV.

Table 1. List of experts interviewed for the study

Activity	Organization	Role within the supply chain
Installer, Second life via insurance claim	Futech BVBA	Futech is a PV installer. In the CIRCUSOL project, they are involved in Cloverleaf and Cohousing Waasland demonstrators. Futech also provides energy as a service models to its customers
Producer	SoliTek Lithuania	SoliTek is a PV manufacturer. In the CIRCUSOL project, they lead the task on PV design for circularity and provide input to other tasks for a circular supply chain
Producer responsibility (2 interviews)	PV Cycle Belgium	PV Cycle is a body for compliance of PV modules waste. Their role is to facilitate waste management and have expertise in organising the collection and shipment of discarded PV modules
Waste management	Veolia Germany	Waste management company offering services like waste collection and recycling for PV modules
Recycling	LuxChemtech GmbH	LuxChemtech, previously Loser Chemie, is a recycler of valuable metals with strategic importance from high tech and green tech waste
Repurposing	SunCrafter GmbH	Suncrafter is a Germany based start-up offering off-grid, upcycled solar solutions for rural and urban regions. In the CIRCUSOL project, Suncrafter is working on a demonstrator
Reselling and repairing	SecondSol GmbH	SecondSol is the online marketplace from Germany for second-hand PVs and their parts, providing services across Europe
Researcher	Murdoch University, Australia	Masters' student, who worked on a thesis titled "EoL routes for wind turbine, solar PV and EV batteries"
Researcher	Australia National University	Professor working on projects related to solar PV deployment and policy side

The interviewer used a set of open-ended questions that were used to guide the interviews but not strictly followed. At times, when the direction of discussion went outside the scope of study questions, the questionnaire helped the interviewer to bring conversation back to the themes of study. The former part of the interview focused on interviewee activities in the supply chain. A supply chain was visualised based on literature review, and it was also shown to interviewees to verify and reflect upon their roles. Depending on their response, further questions relating to understand their roles in the supply chain were probed. This was followed by questions on the material flow such as sourcing, handling, recovery and selling of PV modules. Questions on other kinds of flows such as information and finances came later. The latter part of the interview focused on the different drivers and barriers for their involvement in the second life activities.

3.3 Data analysis methods

The information collected from the interviews was analysed using deductive thematic analysis. In this method of analysis, a set of recurrent themes which come up in the interviews are identified and further developed in discussions. According to Braun & Clarke (2006), this kind of analysis is suited when the researcher already has a theoretical or analytical interest, and the technique outcomes are aligned towards investigating a more detailed analysis of some aspect of the overall data.

In the context of this study, these themes were explained:

1) The role of actors in the supply chain, and their activities.
2) The relationships and exchanges between the actors for fulfilling their role in the supply chain.
3) The influence of different parameters such as logistics and regulations on their activities in general and on developing second-hand activities.
4) The prospects on and their position in future second life activities.

The information collected from interviews was grouped into different activities which they represented. After grouping, the same information was used to identify each activity's respective input and output flows. The flows from each activity were further categorised based on the type of exchanges - material, information and monetary. For each category, the information was interpreted to find the interconnectivity between them. For example, one activity's output flow would become another's input flow (or for multiple activities). Using this method, all the activities were connected using the flows to create a supply chain. During the interviews, a draft supply chain mapping created was displayed and explained. Then, the interviewees were asked to give feedback on it according to their roles in the supply chain. Thus, the supply chain mapping was constantly updated with a constant feedback loop from different interviewees and thesis supervisors. Furthermore, Miro tool (Miro, 2021) was used to visualise the mappings.

3.4 Limitations of the methodology

There were limitations to the methods employed in this study. Firstly, the method of collecting data through interviews. Interviews are a promising tool to evoke perspectives of experts, though there can be a high chance of bias due to limited numbers and less representation of respondents. This makes it difficult to generalise the conclusions of the interviews. Bryman (2012) defines the repeatability of the results of the study following the detailed procedures as reliability of the study, which is an important part of any study design. To ensure that an investigator can understand the question types and the procedure, the general format of questionnaires is provided in Appendix A.

To ensure internal validity of the research, multiple sources of evidence from the literature and interviews were gathered. Internal validity of a study is a measure of how well the study reflects what it is supposed to be denoting (Bryman, 2012). The selection of interviewees was made with the purpose of covering the entire supply chain. Similarly, the literature included both academic as well as grey sources. To overcome such limitations, the results of interviews are typically evaluated using the available literature which are very limited in this subject. Secondly, the self-selection bias of interviewees implies that only those experts would respond to the request who had some level of desire to speak about the subject matter and show their views in alignment with the objectives of the CIRCUSOL project. A conscious effort to discourage a bias in the sample was made by inviting interviewees from outside the CIRCUSOL consortium.

Finally, there can exist a systemic incentive for the experts to only report positive aspects of circular economy if it aligns with their strategic interests. Therefore, a list of five experts outside European context (Oceania) were identified with the help of academic promoter. It was an attempt to bring more credibility to the overall study and add richness to the discussion and policy recommendations. However, out of five experts contacted, only two responses were obtained, and interview with one of them was organised. The information is compiled at the end of Table 1. The responses from external participants did not result in further clarification on the subject of second life PVs. Therefore, the obtained information were omitted from the results and discussion chapter.

4. Results and supply chain

This chapter presents the results of the study and answers the first two research questions.

RQ1: What are the major activities in the second life PV supply chain, and what are the respective roles of actors and stakeholders within the industry?

RQ2: What does the overall supply chain for second life PV look like regarding material, information, and monetary flow?

First, in section 4.1, individual activities in the supply chain are described in detail, explaining the business models identified for each actor. Then, the information from individual activities is used to reflect on the interplay between actors in terms of "share of activity" related to second life PV in the next section. Finally, in section 4.2, the overall supply chain is visualized, depicting three different flows – material, information and monetary.

The reader should note the following points before delving into the results:

- Due to time and resource limitations, the choice of supply chain mapping is limited to the context of European member states and legislation. The other constraint is that the mapping concerns only the second life activities since these are less reported in the academic literature. Figure 13 shows EoL management activities of a PV system installed in the EU, adapted from a decision tree reported by Wade et al. (2017). The highlighted boxes represent the activities of relevance for the mapping exercise in this study due to their involvement in the second life usage of PV modules.

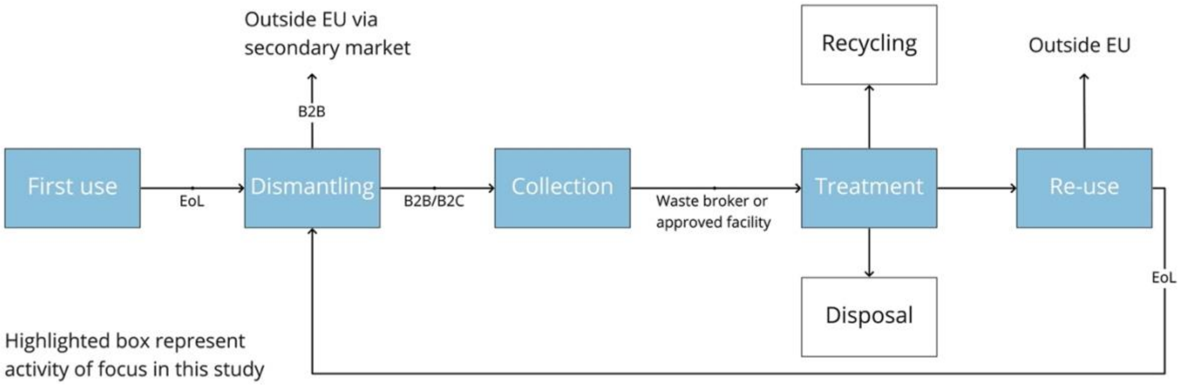

Figure 13. End of life management of PV modules installed in the EU, adapted from Wade et al. (2017)

- The results in this chapter come from the interviews unless mentioned otherwise, and the supply chain is mapped from a market and regulatory perspective in 2020-2021.
- The presented conclusions are drawn up based on information coming from a few selected countries in the EU and primarily from the actors associated with the CIRCUSOL project.
- Countries in the European Union have the liberty and flexibility to implement the official directives into practice. The WEEE legislation (European Parliament, 2012) provides minimum rules and targets across the entire EU member states. Since there is a degree of liberty, the rules transform when each country integrates them into their national laws. Hence, it was attempted to keep the mapping generalized to account for

all the countries but is likely to be biased towards the countries from where the primary data was collected.
- There are different pathways after the first use of PV modules, but none can be fully standardized. Furthermore, some of these pathways are case-specific and not implemented at a large scale. In this study, landfilling is not explored to keep the study focus on circular strategies.
- Since some activities can be organized both on-site and off-site, it is worth mentioning that one actor can be responsible for more than one activity in the supply chain.

4.1 Activities in the second life PV supply chain

The results presented in this section describe each activity in the supply chain and the actors associated with them. The activities regarding EoL PV modules in the EU countries are guided by the WEEE Directive (European Parliament, 2012), which is the European Union's law for regulating the treatment of electrical and electronic waste at the end of their life cycle. The directive has set up the rules for collecting and recycling PV modules since 2012 according to the Extended Producer Responsibility (EPR). EPR implies that the producers are responsible for financing the take-back system and treatment of the EoL PV modules. Producers are defined as designated authorities for completing the administrative and financial duties to comply with the legislation in the EU. The producer body comprises the manufacturers, distributors, resellers, importers, and sellers organizing their selling activities from a distance or using the internet.

4.1.1 First use

The first use activity refers to the operational phase of PV systems until decommissioning. First use can be distinguished in three market scenarios according to the scale of the installation. These are (i) residential, (ii) commercial and industrial, and (iii) utility, and their respective market shares are illustrated in Figure 14. Depending on the different definitions of scale, the industrial scale is often grouped together with utility instead of commercial, which is also the case with Figure 14. The primary reasons for these installations are driven by environmental and financial motives (Palm, 2018). However, the decision to dispose of the modules strongly depends on the PV industry's economic, legal background and technology developments (Gömez et al., 2012).

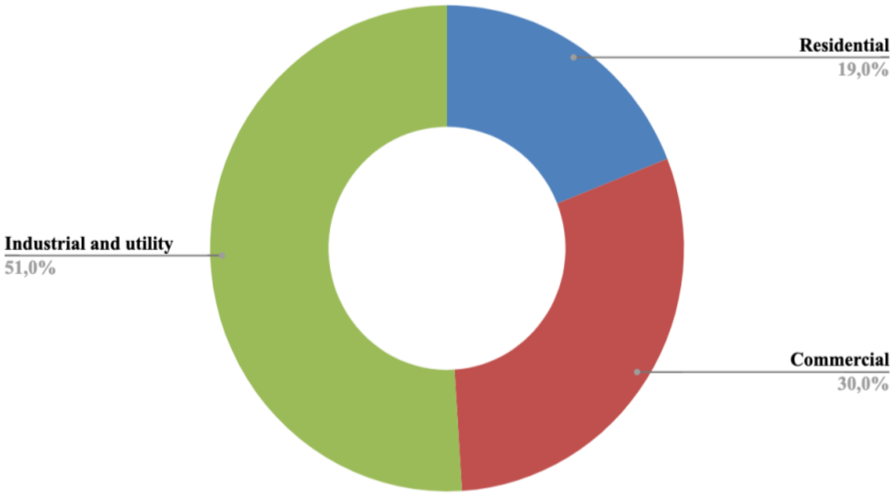

Figure 14. Percentage of installed capacity for different segment in the EU, adapted from SolarPower Europe (2020)

Residential PV systems are characterized by the type of building on which they are installed. Typically, they are mounted at single- or multi-family home rooftops with output ranging below 10 kW. The business model that serves residential first use is ownership of the product, which is the most common in Europe. However, alternatives like buying energy as a service without any product ownership are increasingly becoming attractive. Studies cited in Palm (2018) identified secondary reasons like testing technologies, increased convenience, security of supply, self-sufficiency, and social peer effects for residential installations. Purchasing a PV system is a high-involvement decision requiring time and consideration from the household (Jager, 2006). Due to the complexity of the decision, first use owners may act in accordance with the general practices and as suggested by the installer. Prior to the installation, the installers conduct a feasibility check to determine the potential power output and optimal orientation for the PV modules.

Damage or defect in the PV system is the primary driver linked to early decommissioning in the residential use case. These projects ideally finish their promised operational lifetime of 25-30 years without damages or defect failures. The damages can be caused by storms, hailstorms, or fire, among other reasons. Some of the defects commonly observed include broken glass due to weather conditions, junction box defects and hot spots due to shading resulting in increased temperature of cells. If the first use owner can demand replacement from the insurance, their contractor providing after-sale service is supposed to find a similar module. Since finding similar modules is challenging for technical reasons, the entire array of modules is replaced even if the damage is partial. The insurance institutions also are involved in the supply chain. Typically, the end-user pays for their insurance service and the purchase and installation of PV systems. Beyond damages, the selling of residential property or a part of it with the PV installation can also result in an early decommissioning. When the property is sold, the new party can choose to demolish it, leading to decommissioning.

For **commercial and industrial** installations, the capacity ranges between 10 kW and 1 MW. Industries and commercial buildings consuming a significant amount of energy utilize their unused available spaces such as flat rooftops, parking, and windows to generate electricity using solar PVs. The power generated from the project is supplied to serve their own operations and industrial plants. Installation of PV systems in under-utilized areas such as parking spaces to create solar carports and window spaces to integrate PV with buildings is also observed increasingly. With these kinds of installations, the companies aim to reduce their operations' and their employees' carbon emission.

For both residential and commercial-scale installations, the perceived value of PV systems usually does not decrease fast after their warranty is over. These systems are often used even after their warranty period is exceeded because the energy is generated for self-consumption. However, there can be multiple reasons for the early decommissioning of these projects. Most of the time, it is repowering due to the ageing of components, especially inverters reaching their end of the lifespan. The owner foresees a lack of performance after a certain period of installation. Hence, reasons like upgrading to new technology, falling prices, and changes in policy on solar energy can also be reasons leading to repowering. Damage due to natural hazards or modification in the property building can also lead to decommissioning. For example, when the roofs of buildings require some repairing work due to leakages or changing the layout of the building itself.

Utility-scale power plants are installed to support a utility in meeting its renewable energy production goal. Their capacity typically ranges above 1 MWp with ground-based installation settings, but other mounting techniques are emerging, for example, floating PV on water bodies in Germany, France, and the Netherlands. The advantage of large-scale installations is that the overall operation is optimized, and the operators can efficiently deal with periodical maintenance.

The warranty of the PV systems is a crucial factor for the utility park operators. The perceived value of the PV systems decreases quickly after the warranty period is over as the investor wishes to invest in the least risky system. Hence, the most common reason for early decommissioning a utility-scale PV installation after first use is repowering or revamping. While repowering involves replacing old PV modules and components with new ones, revamping refers to replacing obsolete or damaged modules with increasing the efficiency and lifetime of the overall system. Varying the degradation rate between the modules leads to the system running on the lowest efficiency. There are possible power losses due to some modules. It can be due to shading, technical failure, or damage that occurred at some point. A module with the same power output must be used to maintain overall power and linked feed-in tariff. Even if one module is broken in the system and the installer cannot find the apt replacement, then the entire string or system is replaced instead of replacing the damaged components. The decrease in prices of modules has resulted in the operators replacing the entire plant or several strings rather than figuring out the ones bringing down the capacity and swapping them. It is also possible that the PV modules are installed in a few rare cases but never get connected because the original deal got cancelled for some reason. Decommissioning due to administrative reasons adds to a larger influx of decommissioned modules that are non-defective and functional for a second life.

4.1.2 Collection

The collection is described as a legal activity performed by authorized personnel. After the first use, the PV systems require dismounting and transport to a collection point according to the guidelines of the WEEE directive (European Parliament, 2012). The WEEE guidelines foresee different paths to facilitate compliance:

- Producers organizing take-back system and recycling infrastructures themselves,
- Producers affiliating with existing collective programs,

- Producers integrating PV modules in other infrastructures such as WEEE and municipality.

In this section, the collection activity has been divided into three pathways for postulating a coherent outline – centralized, decentralized and by-pass. These pathways can be implemented differently depending on the national waste management structure, scale of installation and market fit for the used modules. Based on these factors alone, there can be different scenarios visualized for the collection activity as shown in Figure 15. The collection plays a vital role because the point of sourcing of used PV modules is an essential factor affecting the economics of second life activities, further discussed in section 4.1.6

In **centralized collection** systems, the collection of PV modules is primarily centralized and organized by one agency managing the take-back system on behalf of its members. Manufacturers and importers of PV modules form a collective organization to fulfil their legal obligations related to EPR. According to the WEEE directive, the manufacturers and importers of PV modules must ensure the take-back and recycling of their products free of charge (Gömez et al., 2012). Other waste brokers operating legally also exist but at smaller scales and can vary between countries and municipalities in some instances. These also consist of companies not willing to be part of a central system and prefer independence from a collective take-back system in existence, but rather fulfil their obligations individually.

The central driving organization establishes contact with collection and waste management actors to take in-charge of collection and treatment on behalf of their members. The collection for small quantities of PV modules is organized at certified collection points, and on-site service is provided for larger quantities. For example, the collection numbers from PV Cycle (2018) in their annual report show that direct pickups are strongly preferred over collection points in terms of connection channel (PV Cycle, 2018). PV Cycle is structured as a producer responsibility association joined by companies putting their PV in the market as members (Gömez et al., 2012). In this way, the associated members do not require to set up their infrastructures but only report their data to a single organization. The individual responsibility of each company and financial guarantee required by WEEE legislation for future collection and final treatment is taken care of. Hence, there is an intermediary between the manufacturers and treatment actors to fulfil the EPR compliance. The collective efforts of administrative and reporting tasks to the national WEEE register are also handled. Therefore, the centralization optimizes the efforts and yields higher benefits in terms of organization for the members of the collection system. Combined with other actors organizing collection at a smaller scale like waste brokers, the overall collection information is submitted to the national WEEE register.

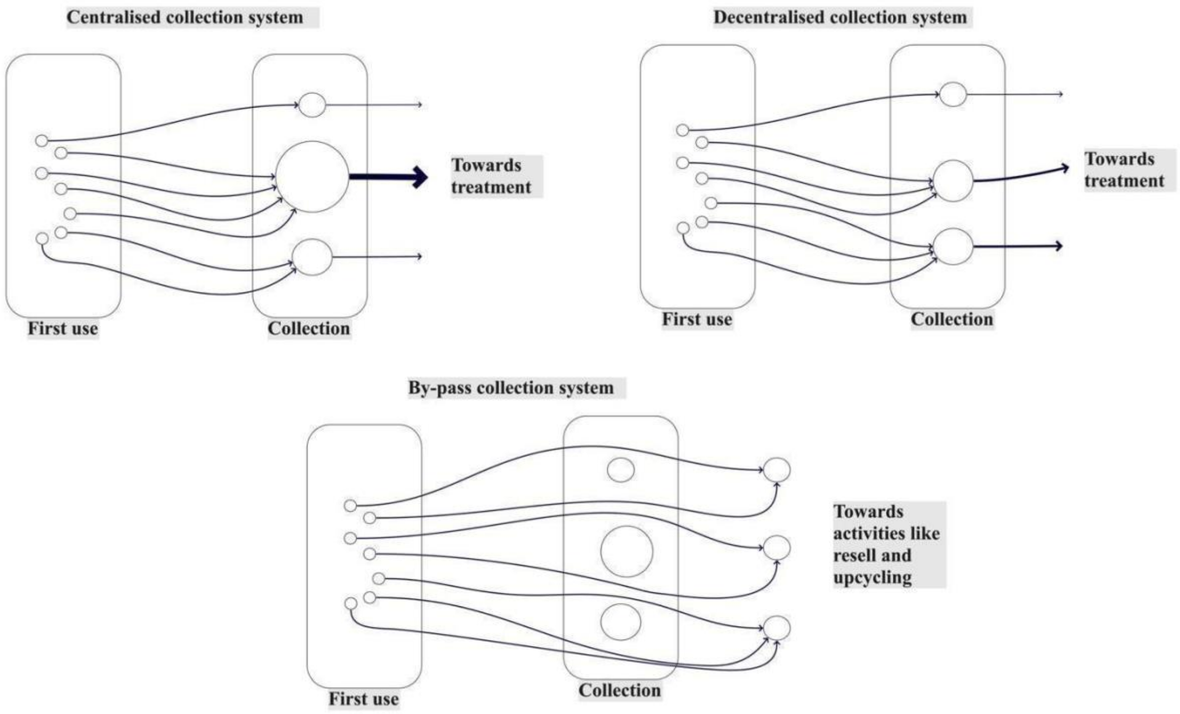

Figure 15. Different types of collection systems visualised to show the general idea (author's elaboration)

There is no single organisation in charge of the reverse logistics or take-back system in a **decentralised collection system**. There exist several actors, including PV Cycle, who organise take-back systems at similar scales. Hence, the collection of PV modules is not managed by one single agency or intermediary but rather directly by the national WEEE agency. Contrary to the centralised system, the EoL modules are collected at the collection points from private and public agencies such as local municipalities instead of one intermediary. For larger quantities, the owners can directly contact local collection agencies and organise an on-site collection. Like centralised systems, the manufacturers directly establish contracts with reverse logistics organised by waste management companies to take in-charge on their behalf for collection and treatment. However, these contracts are not observed in a collective scheme where the intermediary actor sub-contracts with waste management companies.

For example, in Germany, there is a possibility to drop off twenty modules without a fee at a local dedicated waste disposal site for residential owners. The city administration typically manages the collection points. The national WEEE agency (EAR) coordinates EoL management and integrates the overall information in its database. EAR does not collect money for the organization, which is the case of a central system like PV Cycle, but instead regulates the waste management responsibilities of manufactures and importers. Based on a ranking of companies on the number of PV modules put in the market, each company is responsible for managing the proportional amount of PV modules they introduce. This system implies that it is not always the initial manufacturer who is responsible for their modules. It is also possible that some of the companies are insolvent to take responsibility for the EoL management of their module. Therefore, the take-back system is centred on the number of modules the company puts on the market every year.

The drop off system works satisfactorily for the residential scale. However, there are complications in B2B scenario because of the large scale, and many manufacturers do not exist anymore. In the European market, especially in Germany, the PV industry expanded very quickly until 2010, but after that period, many companies declared bankruptcy. The local legislation in place is also adapted in some countries with time. For example, there can be two scenarios discussed in Germany depending on the installation period of the PV modules – pre- and post-2015. For the former case, the legislation holds the site owner responsible for final treatment. Due to the apparent fact that most of the modules currently getting decommissioned were installed before 2015, it is the commonly observed case. For the latter case, the manufacturer is held responsible.

Alternatively, some actors in the supply chain can **bypass** the collection agencies organizing take-back systems. Multiple scenarios can be developed based on the actors involved in the exchange and the distinction between the second life use and final treatment modules. In addition to the first use owner, the other actors with direct involvement are reseller platforms, companies repurposing the modules, second life PV owners and insurance companies. The guidelines to regulate reverse logistics for second life modules do not exist, which is why involved actors take the lead in deciding their logistics. The supply of PV modules in this kind of system is attributed mainly to non-residential actors. By-passing the intermediaries shortens the supply chain for them, resulting in faster and cheaper logistics.

The first use owner can directly approach the first treatment plant for collection and EoL management for large-scale installations. Similarly, direct exchange between first use owner and resell actors is also observed, especially for medium to large scale installations. Such scale is preferred because it provides the benefit of economies of scale, ease of collection and homogeneity of the modules. The first approach between these two actors is followed by exchanging visual and technical information about the PV systems before the modules are collected for transportation. The emergence of online platforms for direct reselling has formalized this exchange activity to a certain extent. However, illegal activities also occur and are discussed in Box 1.

Some manufacturers keep a stock of old modules to meet the replacement demands following insurance claims. Similarly, companies providing after-sales services sometimes stock functional modules in their inventory. These are directly collected from the site when the first user encounters a problem with their PV system. When the modules are demounted from the rooftop, they are already visually sorted to have a clear view of which ones can be further used.

Box 1 Illegal collection

This box describes the illegal activities during the collection of first use PV modules. Due to the leakage, most European countries fail to achieve the collection target set according to the WEEE directive (European Parliament, 2012). If actors collect these modules without legal paperwork, the modules are not reported to the national WEEE register and often transported to other countries as second life modules. The transported modules have almost no warranty and a low amount of working years. Furthermore, the lack of a sound recycling system in the destination countries become a big waste problem.

Even a central take-back system from PV Cycle does not ensure that all the modules must be collected via them in countries like Belgium and France. The other options are also allowed if they are authorized. This can lead to unauthorized collection activities, as witnessed in the real-life scenario. For example, the authorized collection points and residential owners are occasionally contacted by illegal collectors for purchasing PV modules without any paperwork.

Changes in national regulations make the site owner’s responsibilities less clear. In an interview, it was reported that the park operators, at times, prefer to export their PV modules to other countries (both inside and outside the EU) rather than paying for recycling. A few of the possible reasons are that the treatment represents a cost for their business activity. There is a lack of awareness of changes in legislation, which are often not trickled down efficiently. The confusion is caused primarily due to the legislation holding the treatment responsibility depending on the date when the PV modules were placed in the market. Exporting low-quality PV modules to countries without any e-waste regulations implies dumping the waste.

4.1.3 Preparation for final treatment/second life

There are three fates which the collected modules commonly follow: recycle, second life and landfill. In order to understand and decide which strategy should be applied to the collected modules, they need to be inspected. The inspection can be visual and later followed by advanced techniques like applying electrical measurement to test the functionality and performance. The inspection of modules is straightforward when they are already decided to be recycled. However, an elaborate process is required to prepare them before introducing them to one of the second life activities. The preparation activity can be defined as a predecessor step to final treatment (recycling), landfilling or second life and illustrated in Figure 16.

During the preparation for the final treatment, the aim is to follow the legal obligation to check the functionality of the modules to obtain a clear idea of reusability. Hence, preparation activity is an added step observed between collection and the final treatment process of recycling. According to the WEEE directive, the treatment of EoL modules is ensured by the producers, including manufactures and importers. The functional modules eligible for second life are pushed for second life activity. The final treatment stage modules are considered non-functional and recycling to valorise raw materials is the most preferred treatment method presently. Both preparations for the final treatment and the final treatment activity can share the same operation site. Based on the condition of the collected modules, this intermediary step can be omitted when modules are damaged. In the case of a warranty claim, a similar preparation activity for inspection and repair is also followed by the manufacturers or contractors providing after-sales services (Weckend et al., 2016). For second life modules, which bypass this preparation stage, a similar inspection process is commonly followed before being sold either offline or online, called preparation for second life.

Preparation of modules for second life consists of three significant steps - inspection, testing and labelling. The modules that get sorted as functional according to the warehouse's preparation steps enter the warehouse and get listed in the inventory. Repairing or replacement of components is also pursued when necessary and feasible. According to SecondSol (2021), repairs are possible for the cases of broken bypass diodes, junction boxes, module frames, back sheets, module cables and connectors. The modules eligible for second life applications are mainly resold as a replacement (Weckend et al., 2016). This approach also goes along with the circular economy principle of using a product's functionality to the best possible extent (Potting et al., 2017).

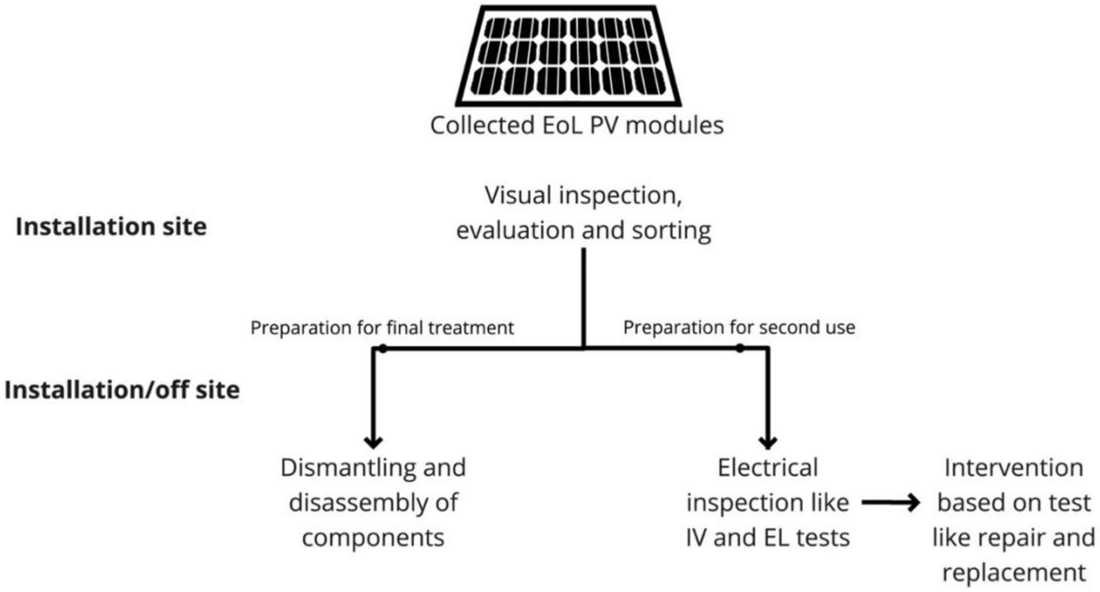

Figure 16. Simplified illustration of preparation steps followed after the collection of decommissioned modules (author's elaboration)

Futech (2021) has illustrated a complete decision tree to show how these tests are organised. Firstly, the primary components of the module such as glass, DC cables, frames, junction box and cells are visually inspected for physical defects. In some cases, the basic visual inspection can start directly on-site during collection. With a simple visual inspection, collection staff can easily identify the defects like broken glass, delamination of encapsulant materials, broken frames, hot spot indications, charred electrical connection box, surfaces altered due to weathering and defects in connectors. However, the visual inspection requires physical labour, so it is preferred for commercial and utility-scale installations but not residential. The collection from residential scale requires more effort because of the low volumes, geographical distribution of collection sites, and low homogeneity of module type collected. The modules that do not show physical damage are approved and sent to the next step for electrical tests, where the machines can identify a range of defects invisible to the human eye.

The two main tests to identify electrical condition of PV modules are electro-luminescence (EL) test and IV curve test. These tests are generally conducted at a manufacturing or recycling facility hosting dedicated testing equipment. The EL test uses specialized imaging equipment and current flows for checking inactive strings and microcracks. If some modules require fixing of components like junction boxes and cables, these modules are fixed and approved for further testing. The remaining modules which show signs of defect and damage are directed towards recycling. In most cases for thin film modules, the degradation is so high that second life options are not possible. Next, the parameters related to PV module performance are tested in a flash tester using a current–voltage characteristic, or IV curve test. The ones which pass all these tests are labelled according to their performance and sorted before entering the warehouse for storage or further transported for second life applications. The modules reaching the warehouse storage after the preparation stage are registered and deemed eligible for second life.

The preparation success rate can be defined as the percentage of modules that pass all the functionality tests and become eligible for second life application. The success rate depends on several parameters and directly affects the cost of second life modules. Four primary parameters which affect the success rate as interpreted from the interviews are (i) prevailing conditions of the PV module, (ii) point of sourcing in the supply chain, (iii) market use requirements and (iv) handling of reverse logistics.

Prevailing conditions of PV modules such as the age, physical built, quality, and historical performance are directly related to their success in future applications since PV modules have a limited operational lifetime. Low module age, strong physical build, high manufacturing quality and performance would imply a higher success rate. Physical damages and defects are often the reasons why PV modules are discarded at an early age. **Point of sourcing in the supply chain** is also an important parameter determining the success rate of the preparation process. As discussed in the section on collection, the reverse logistics can be easily organized for large scale installations and the collected modules are similar in their build and performance. Processing a mix containing several types of modules can be labour demanding and the preparation process would require frequent adapting to different module types. Therefore, the success rate is supposed to be higher when the modules are sourced at a utility power plant compared to residential collection points. Sourcing from the latter case increases the number of actors, which can be easily by-passed with direct on-site collection from utility operations. The conditions which PV modules are supposed to meet is decided by their **market use requirements**. Preparation process for PV modules intended for energy demanding applications such as high voltage AC require to meet stricter performance criteria compared with modules intended for off grid battery charging. Labelling of inspected modules becomes important for grouping them according to the results of their final tests. The overall **handling of reverse logistics** including transportation of PV modules also affect the success rate. If the modules are not carefully transported, they can develop microcracks and other defects, leading to a lower percentage of modules eligible for second life. Hence, the actor in-charge for reverse logistics plays a very important role in augmenting the success rate.

Increasing numbers of park operators and waste management companies are exploring the possibility of second life to secure capital by selling and avoiding treatment costs. However, it should be noted that the preparation process generates costs too. The cost for preparation is high because the process is not very optimized because the volume of decommissioned PV is not large enough. In addition, the business model for preparation activity or the final treatment in general is very different from selling the PV modules. Whether these waste management companies prefer to sell the functional unit themselves also depends on their strategic vision while considering the limited resources at hand. Today, preparation is typically organized by a waste management company, which is not characteristically built to spend resources on preparation of modules and selling them. According to the interviews, some of these companies decide to sell modules via direct reseller platforms or get approached by interested buyers with specific requirements for second life PV modules.

4.1.4 Final treatment

The final treatment stage provides for the processing and treatment of non-functional PV modules intended for safe disposal. In terms of the waste management model, recycling is preferred at this stage, providing raw materials for the manufacturing of new PV modules or other products. Waste treatment companies undertake the recycling process of EoL PV modules. Since there are only moderate quantities of PV waste in the current market, companies invest in demonstration projects rather than dedicated PV recycling facilities. The current recycling processes may not recover the materials thoroughly, but the current strategy still offers legal compliance without the need for new recycling investments (Weckend et al., 2016).

The existing recycling process is based on mechanical separation of the major components and materials of the PV modules, followed by a combination of thermal, chemical, optical and metallurgical steps. These combinations can vary depending on the type of PV module and the required material output quality the recycler envisages. Section 1.4 describes the recycling process in terms of the input-output process flow. In mechanical separation, the major components like glass, polymer, aluminium, and copper are separated and follow their specific recycling path. Laminated glass from silicon-based PV modules follows a process like flat-glass recycling while the metals can enter their own established recycling loop. Polymer components are generally processed in waste-to-energy units to produce energy. The remaining material, such as silicon metal and silver, require more advanced processes. Similarly, for thin-film PV modules, the recycling process combines mechanical and thermal, optical, and chemical steps. These processes result in the separation of Tellurium and Cadmium products in addition to the laminate glass material.

The primary business activity of the final treatment is processing the PV module waste. The secondary activity of selling the material output from the recycling processes as raw material input is also highly observed. The recovered materials often suffer from high impurity levels, which could reduce the selling price. For example, the recovered glass from a silicon PV module can contain silicon, polymers, and other metals. Such high contamination level glass does not find direct applications and is often blended with other recycled products. The other valuable components in a PV module are present in very low percentages. During the interviews, the possibility of engaging in other activities such as collecting and selling modules for reuse was also observed. For a classic recycling company, dealing with logistics is a new step, and conventionally, an external party is contracted to organize a collection for them.

4.1.5 Reselling and repurposing

Before the PV modules are available for the second life market, several steps are involved to augment them for their market fit. These steps involve intermediaries for organizing resell, repair and repurposing. These vary depending on the actors and their business models, but for these activities, there are no standard norms or guidelines set currently. These actors procure functional modules meeting their use requirements and make them fit for the second life applications according to their business model. In case some of the modules are not suitable or damaged, these are sent directly to the final recovery stage for recycling. It is important because there is a risk to have double counting of modules in the total collection register depending on how the information transfers to the national WEEE register and how these modules are categorized.

Reselling can be defined as a reuse activity for second life PV modules. The functional modules after their first use can be resold as used modules in the market at a reduced price. The application for these second life modules can be either as new installations or as replacement. Such an exchange requires an intermediary to connect two parties for exchange. In recent times, several platforms for online reselling have emerged to support these exchanges. In these platforms, an owner can directly list their PV system and establish a buyer-seller agreement with another party interested in their modules. Since a modest market for these second life modules is already emerging, these resell platforms sometimes purchase and stock decommissioned modules which are functional for second life. Examples of these virtual exchange platforms are SecondSol and pvXchange. With higher number of PV installations and early decommissioning, the market for second life modules is observing more quality equipment and is projected to increase in near time.

PV modules for resell can require some form of repair or replacement of components. If such interventions are not required, they are considered for direct resell. Modules sourced directly from the site of utility parks or commercial installations follow an inspection and testing process like the one described in the preparation for the final treatment. The activity can be called preparation for second life because it is organized by actors organizing a second life market. When the repairing is feasible, the common activities for it involve replacing the frame, junction box, diode, plugs, sockets, and even solar cells. Re-lamination of the modules is also an option. These activities require the modules to be relabelled with new specifications and guarantees according to the legal system and sometimes even another brand name for marketing purposes (Weckend et al., 2016). The resell modules are often relabelled and the companies which register them as producers take the charge of EoL responsibility.

Repurposing is also feasible with second life modules and is increasingly getting attention by companies interested in new market segments. It enables reuse of PV modules in a different function than it was originally intended for. Currently, these segments are often related to standalone off-grid applications, for example charging batteries of mobile phones, electric bikes, and electric scooters. PV modules which are not capable for high voltage AC applications make a good case for off-grid standalone use. Other off-grid applications include a secondary power source for events and holiday homes.

The companies sourcing second life modules for repurposing typically source directly from the site, hence, the by-passing collection pathway is followed. The module comes directly from the first use owner, insurance companies or even direct reseller companies. At times, the park operators can also donate the modules and transfer the disposal responsibility to these companies. Purchasing the functional modules from the stage of preparation for the final treatment is also an option for these companies. Preparation success rate defined in section 4.2.3 determines the cost of second life modules. Depending on the proportion of modules eligible for reuse, the economics of the further process is established. For example, if 50% of the total modules purchased are broken or not eligible for further reuse, then the overall costs will be higher due to extra purchase and handling. The upcycling companies also have the option to purchase the modules from direct reseller platforms.

4.1.6 Second life

Second life applications for PV modules depend on the use case and requirements of the customer. The commonly observed use case pathways for the second life PV modules are residential installation, standalone off-grid, commercial and O&M market. The specific requirements can vary between these use groups but common functionality parameters like having the same range of watt peak, good shape and efficiency of the module are the same throughout. Due to degradation in performance over time, the second-hand modules offer less power density, meaning they generate less electricity per unit area of installation. Therefore, it is typical that the second life PV owner require large space for installing the modules, for example at farms or mining sites.

Similarly in the case of residential property, one of the requirements is that the roof potential of the installation must be higher than the energy consumption. For the fact that most common rooftops are pitched, the installation should also maintain a uniformity for aesthetic reasons. For medium to large scale installations, such as in commercial buildings and industries, the main driver for installing second life PVs is the returns on investment for renewable energy generation. Companies which want to generate renewable energy at a lower cost prefer this option. LCOE and internal rate of return (IRR) of the project is considered in the planning phase of installation and the total cost of ownership (TCO) should be lower compared to the new modules. Even though the installation is for self-consumption like residential, less importance is given to the aesthetics in this case. In fact, pitched rooftops are less encountered in industrial buildings. Standalone off-grid use is preferred for cases not demanding high intensity output, such as charging batteries of mobile phones and electric bikes. Similarly for the O&M market, the second life PV is interesting when replacing a single or few modules which have the same current output as the other modules in the string. If no such replacement modules are found, the entire string is replaced.

The price of the second-hand modules also depends on several factors but should typically be lower than the new market prices around 50-75% less than the original. The second life PV owners can be considered price conscious but are willing to pay higher prices for buying a replacement which is rarely found in the normal market. Finding older replacement modules to match the ones in their existing solar arrays can become challenging for the installers. However, it is possible that these modules are available and listed on online exchange platforms. The factors which determine the costs of second life modules are the same as the ones for “preparation success rate” because it determines the process of inspection and testing of modules before they are sold in the market. Age of the modules and efficiency level are central to determining the price of these modules. Other factors include the warranty conditions and aesthetic appearance.

4.2 Supply chain mapping

The methodology for the systematic mapping of the supply chain was introduced in section 3.3. In this section, the results are presented in the three following subsections illustrating the flow of materials, information, and funds. These three aspects form the most important flows in the supply chain, hence, are selected to be mapped separately. Separation of each type of flow also enables one to view the supply chain with clarity, although there are several interlinkages. Often, the material flow is documented in the general research studies, but it is driven by exchange of information and money which makes it crucial for understanding their interlinkages. To pay particular attention to the second life of PV modules, the scope of the mapping is set right after the PV systems get dismounted from their first use case. The general supply chain is documented in the literature, but the second life supply chain finds no mention. Hence, the scope of mapping was limited to create emphasis on activities after decommissioning of PV modules from their first use. The supply chain is followed till the PV modules reach a second life activity or EoL disposal e.g., recycling or landfilling. The upstream supply chain of PV modules till their first use is already well documented in the literature. In the mapping figures, the text on the arrows depicts the drivers leading the specific flow path to the next activity.

4.2.1 Material flow

The flow of material in the supply chain illustrated in Figure 17 corresponds to flow of PV modules. In the mapping, the thickness of the flow arrow represents relative volumes, however, not to scale. Due to the different scales of operations, some activities are organized at the same site while at other times, the modules are transported from one activity site to another. The main reason to reduce the movement is to decrease the overall costs in terms of transportation and labour hours. In large scale installations, it is easier to organize initial inspection at the same time as decommission. On the other hand, performing inspection at every residential household would lead to inefficient use of time, resources, and money.

The first use of the solar PV systems was described in 4.1.1, which can be broadly classified into utility, commercial and residential according to their usage and scale. The factors leading to decommissioning for each of them vary depending on case but can be classified as either need-based or incentive-based. Decommissioning of the PV modules because of damage, defect, age, or performance can be considered as need based. On the other hand, the owner or operator can also have an incentive to decommission PV modules such as for repowering or revamping the utility park. The decommission activity is organized by authorized personnel, which can be the original installer or an external party. For large scale installations, the owner considers between two EoL treatment options for the decommissioned modules – either introducing them to second life or sending them to final treatment (recycling or landfill). Depending on the parameters such as the scale of installation, age and underlying performance, PV systems enter the established collection stream or bypass this stream to enter the second life market, as described in the section 4.1.2 on collection systems.

The collection activity in the centralized system is organized by the collective producer responsibility agency such as PV Cycle. These collected modules are then transported to the waste management contractor. In the decentralized system, the modules lie in the collection points at municipality level or directly at the site of nearby waste management companies. Majority of the decommissioned PV modules follow these two systems. In the third scenario, the individual actors organize the decommissioning and collection activity, and the modules are collected by them, thereby bypassing the established collection system. Since the by-pass scenario is structured around individual actors, it is still organized at smaller scales compared to the well-established collection systems. In cases when the authorized collection is not prioritized, illegal collection leads to leakage of material from the supply chain (see Box 1).

After collection, the PV modules follow preparation activities, which can be typically described as a sorting and testing process. The objective of this activity is to sort the modules based on their functionality for either reuse or recycle. A general flow of the process is described in 4.2.3, which the actors adapt depending on their intent of operations. The visual inspection can lead the PV modules to different pathways, and likewise the process can be augmented either preparation for the final treatment or preparation for second life. Preparation for second life is also a testing process where the PV modules meeting the functionality criteria of reuse are shortlisted and the rest are sent for recycling. The functionality criteria for PV modules eligible for reuse consist of module rating, power output and current output. Currently, the majority of the PV modules are sent to the final treatment step for recycling. The damaged modules often do not meet the reuse criteria and the market for repaired second life modules is still in early stage. In some countries where the legislation permits landfilling, the modules can also be directly sent to landfilling. One of the largest dedicated c-Si PV module recycling facility in the EU is operated by Veolia and PV Cycle. The facility was set up with an annual recycling capacity of 1300 tons in 2018 with a target of processing 4000 tons in 2022 (Veolia, 2019).

When PV modules are not collected in one of the two established systems, they are bypassed by actors aiming to organize activities, mainly related to reselling (or repurposing) the PV modules. In some cases, the producer companies providing maintenance services take back the modules directly following insurance claims and reuse them in the future, if applicable. The reselling of PV modules is conducted by the parties involved in the exchange deal. Online platforms for the same activities are also becoming popular. Some of these platforms also purchase the PV modules for further selling to their clients and provide repair services for the modules and their components. Before selling the second life modules, the preparation process is followed by performing inspection and testing. When the repairing is feasible and required, the internal treatments such as repairing of components or even replacement is performed. In this way, the PV modules depicting functionality in terms of performance are introduced again in the market by the reselling actors. Aspects like economy of scale and market acceptance also affect the resell market in terms of demand and price of the second life modules. The companies selling modules for reuse also source from waste management companies after they pass the preparation for the final treatment process. The waste management companies and resell companies establish demand-supply agreements for the functional modules to join the reuse stream. A similar path is followed by modules which are repurposed by the companies and introduced in the market. Repurpose activities require some form of intervention in how the modules are made to fit their second life market applications. The second life modules are installed by an authorized installer, like in the first use case.

The applications for PV modules entering the second life depend on their use case, which can be broadly grouped into residential installation, standalone off-grid, commercial and operations and maintenance (O&M) markets. Most of the time, these applications use the modules listed on the second life market. In the interviews, it was noted that the utility scale installations using second life modules are less encountered due to high land use requirements. When the space is available, for example on the mining sites, it is still feasible to install medium scale installation with second life PV modules. Modules repurposed into a new product are sold as standalone off grid solutions for niche markets like electric battery charging or energy solutions for event set-ups. Actors providing after-sales services purchase second life modules for their maintenance services requiring repair and replacement. In the event of an insurance claim as well, the PV modules are reused for O&M purposes. Often, the entire arrays are replaced even when some modules are functional. Therefore, some producers and installers prefer to store the functional modules after an insurance claim. These modules follow a modified form of preparation for the second life process and come to use in case of future damage in other place.

Given the WEEE regulations, the producers can operate an independent take-back system or become a part of a producer compliance scheme, like the one from PV Cycle. The mapping suggests that there exist limited options to extend the lifetime of PV modules, either by maintaining them in their first use or introducing them for second life activities. Even when the PV modules are recycled, the recovered materials should be used in PV modules to the full extent to promote a circular economy.

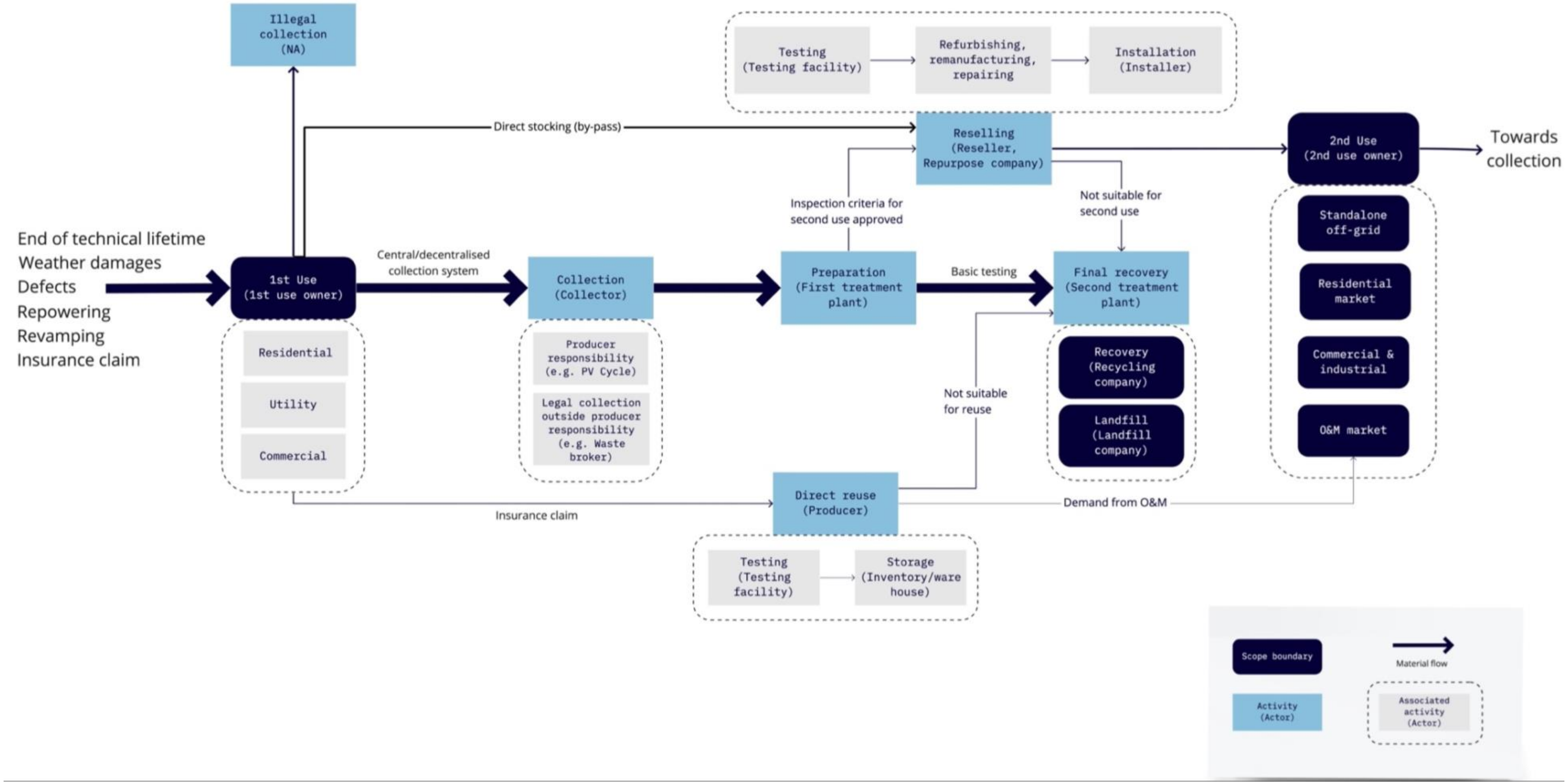

Figure 17. Material flow mapping (author's elaboration)

4.2.2 Information flow

Exchange of information plays a crucial role in determining the flow of material. Since the information can correspond to a variety of knowledge being transferred between the actors in the supply chain, it is more complex to define compared with the material flow. The information exchanges also move back and forth unlike material. The most common information which is exchanged is the specifications of the PV modules and the details related to the historical and current performance of PV systems. To organize the mapping in a coherent manner, only the most important information flows are illustrated in the Figure 18 below.

After the first use, the owner contacts the authorized personnel for decommissioning the modules and provides the information for demounting and collection of the PV modules. Now, the collection can take place in different ways depending on the intention of the owner. If the modules originate from a manufacturer enrolled in a collective system like PV Cycle, then the information is typically sent directly to a collection point for organizing pickup or direct drop if the installation scale is small. Only the PV modules coming from a producer who is a part of the collective system are accepted for free, otherwise a small fee is incurred. In the decentralized system, the first use owner can contact their installer or waste broker agency to organize collection pickup or drop directly at their local collection point organized by municipality up to a certain number of modules. Direct pickup is commonly observed when the scale of pickup is large, i.e., commercial and utility scale installations. The original producer of the collected PV modules is registered in the official WEEE database of the country, which is later used to organize the downstream activities and reporting. In both collection systems, the producer origin of the PV module plays an important role. The overall information from the collection activity is handed over to the national WEEE register. The other route in which the information bypasses the “primary” collection system is when the reseller (or repurpose) company organizes a direct pickup for the PV modules from the medium to large scale installations. This kind of collection activity is organized when the first use modules are eligible for reuse and meet a set of quality criteria required by these reselling (or repurpose) actors. These criteria refer to the functionality of the PV modules, their build quality, performance and fit for use for the intended second life application. Therefore, this kind of information gets exchanged between the two parties before the purchase of the modules is agreed. In cases when the authorized route is not followed, the modules and information associated with them is not collected in the system, resulting in leakage of the material as well as the information.

After the collection of PV modules, a preparation activity is followed to inspect them for their functionality. This activity can take place at the site of PV decommissioning or an external site. The general flow of the preparation process is explained in the section 4.1.4. If the process is organized by the waste management company before recycling, it is called preparation for the final treatment. The objective is to use inspection methods to sort the non-functional modules which would go to the recycling process. The functional modules are attempted to be introduced for reuse activities by selling them to the corresponding actors. The information about the functionality combined with existing information about the panel is used to sell modules to the reselling partners depending on their demand. This knowledge is used to organize the step of final recovery for the modules which do not meet the reuse criteria. Information about the type of PV module is important to optimize the recovery process. Silicon-based modules are treated in a different recycling process than the thin-film modules. However, this kind of sorting takes place in the first step of collection itself with the visual inspection. The material output from the recycling process is classified according to their purity. This information is further used to define the efficiency of the process and organize the further selling of these secondary raw materials in the market. For example, the glass obtained from the recycling facility can be sold for different applications depending on its purity and level of contamination. For the final treatment process of recycling, the reporting of numbers is made mandatory if the recovery facilities wish to secure certification for their technology.

The type of information used to organize activities like reselling (or repurposing) and reusing after insurance claims are the same. After sourcing the modules, the reselling actors organize different activities to further create knowledge about the performance of the PV system. With this information, the actors facilitate additional activities such as repairing, refurbishing, remanufacturing or even upcycling. Based on the information about demand and supply from the market of second life PV, the reseller or second life PV companies organize their sales and other associated activities like installation. The second life following an insurance claim generally requires the responsible producer to follow similar activities when the insurance provider receives and transmits the information of a claim.

The mapping of information exchanges along the supply chain shows the complexities involved with it. Furthermore, it poses even higher complexities for the systems with decentralised design since the information network depends more or less equally on each actor. The responsibilities for waste management can likely get affected if the communication between private companies and manufacturers is limited. The regulations for preparing modules, especially for the testing, standards, and certification process, remain unclear. Hence, the lack of information flow can be one of the likely causes for limited cooperation leading to reduces developments of second life PV market activities.

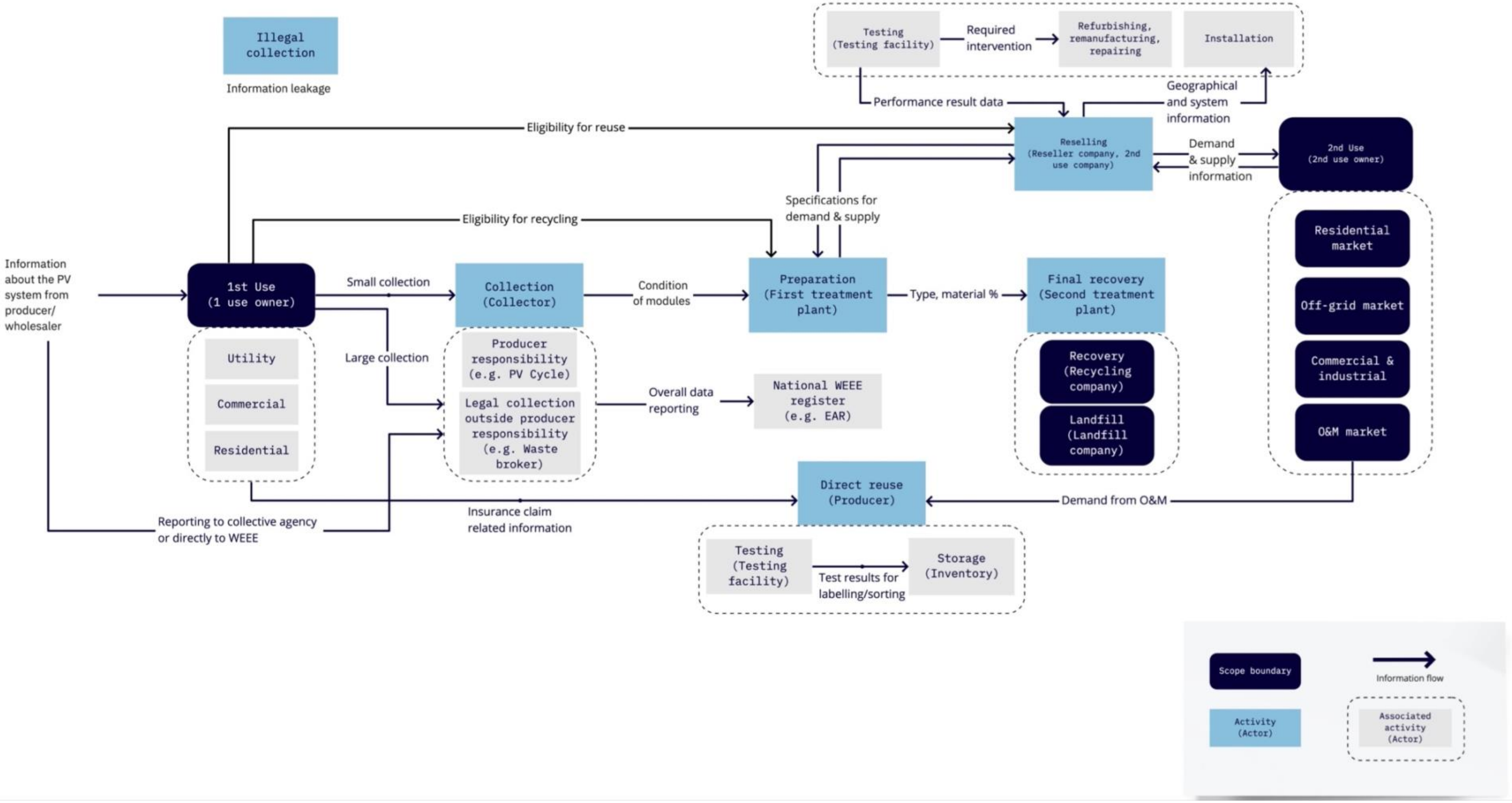

Figure 18. Information flow mapping (author's elaboration)

4.2.3 Monetary flow

Monetary flow is the flow of funds, money in one form or the other, between actors offering/acquiring services and/or materials. In this case, the material consists of PV systems in one form or another, and the primary services comprise of collection, transportation, testing, repairing activities, material recovery, operation, and maintenance. Like the material and information, the monetary flow extends outside the supply chain under study. The monetary flows between the different actors are visualized in the following Figure 19.

After the first use owner purchases a PV system from the producer and pays for the associated services like insurance, the only monetary flow in the outward direction points at decommissioning and collection towards their EoL. The cost for decommissioning and collection of PV modules is the only common costs applicable for both the final treatment and second life. These costs depend on the scale of installation and the fate intended for the modules. The costs for modules intended for second life are likely to be higher since they require careful handling and inspection. Typically, at a residential scale, the primary collection does not require a fee of up to a certain number of PV modules. In most cases, the producer responsibility agency monetarily supports the collection activity, e.g., PV Cycle. For example, in France and Belgium, the collection is organized on behalf of the PV Cycle. A collected recycling fee is used for funding the administrative, legislation and EoL management activities. Such agencies get monetary support from the producers who opt to partner for EoL management. A fixed EoL management fee is paid to the installer, which is then transferred to the wholesaler or producer. These are used for organizing take-back after decommissioning the PV system. The fee is transferred from the installer or wholesaler to PV Cycle. After transferring the EoL management fees, the producer still has the legal responsibility to fulfil, which is taken care of by PV Cycle both operation and finance wise.

The EoL management includes preparation and final recovery process, which also receive financial support to organize their activities like recycling or landfill in some cases. The preparation stage is a predecessor to the final treatment and some of the costs encountered are typically coinciding with recycling process. For example, the take-back costs dependent on the point from which the modules were collected, where they were sent, and the cost of labour are factors attributing to the costs for the recycling process. In the scenario when the owner decides to send the modules to final treatment, then only the costs for recycling or landfilling are observed. These activities also require a gate fee, which varies from one region to another. When the PV modules are inspected for their functionality during the preparation stage, it is possible that interested companies can acquire them for reselling or repurposing. The inspection and sorting activities entail costs in terms of labour and specialised equipment.

The first user can benefit from direct purchase of PV modules by second life PV companies for medium to large scale installations. For the supply side activities bringing the PV modules to the second life market, the primary costs come from sourcing the modules, testing process, repairing-related activities, storage, and installation. From the side of the park operator selling used PV modules, the selling price can be considered as profit and the associated interventions as costs. The intervention costs for preparing second life modules can be cleaning, handling, repairing, testing and recertification. These often depend upon the underlying condition of modules, installation scale, and local labour costs. The costs will be lower for healthy modules than the modules requiring additional repairing or replacement of the component. For large scale installations, the testing can benefit from automation. An interviewee reported that a fully automatic EL and IV curve test could cost 15€ per module or less, but the same testing can reach up to 100€ if manual intervention is required. The fixed costs include machinery for testing, and variable costs are for labour and repairs. SecondSol (2021) reports the module repair costs depends on the number of modules and type of damages, and it can vary from 21€ to 88€ per module. The source of revenue for these companies comes from providing the product and services to the second life PV owner. The second life PV owners willing to install PV modules look into the total cost of PV system installation, considering the amount of power and lifetime remaining in the system. The end-users looking for investment rather than self-consumption would also consider the fluctuation in grid prices, affecting their revenue. The monetary flow regarding the illegal collection activity is less documented. However, these material leakages from the supply chain are operationalized by paying a certain price to acquire the modules.

Similarly, for the insurance claims requiring the producer to provide O&M services, the costs are fulfilled by insurance providers and external O&M requests at certain times. The economic value of final recovery is currently lower than the value of functional second life PV modules. The resource recovery process requires energy and material input for the creation of raw materials and transporting them. The economics can vary depending on operational costs and the value recovered materials generate on the market. As discussed in section 2.1, most of the material in a PV module is glass, which is sold cheap due to degradation in quality. The glass is sold immediately to avoid overflow and storage costs but still incurs transportation expenses. During the interviews, one of the recyclers mentioned that the current waste stream is not big enough to invest in a new plant.

The remaining modules are recovered for secondary raw materials or energy in some cases, which form another source of income for the final treatment activity, typically performed by the recycling agencies. Recycling processes differ in terms of their input material, the process itself and the outputs it yields in terms of material. The economics of recycling is still in the development phase of viability. Today, the market is structured in a way where the manufacturer must pay recycling fees to the EoL treatment companies. The majority of the recycling facilities can be regarded in the demonstration stage, between 10-50 tons in a single project. Since a lot of these waste treatment facilities are not specialised and have straightforward processes, it is observed that the module components and parts, after a few steps of separation, are cascaded from one recycler to the next for the final separation step. Therefore, it is too early to discuss the financials of a recycling plant without considering the maintenance and labour cost over one year of running. The overall recycling process must be supported financially since only the outgoing flow of secondary materials cannot sustain the operations. The valuable materials present in minimal quantities are difficult to recover. If these constituent metals can be valorised effectively, the overall ratio of cost-to-revenue for a recycling process will also improve. Currently, recycling costs can be firmly attributed to geographical location, cost of labour, collection and processing points, the complexity of dismantling, separation process and further costs for purification of retrieved materials. *Landfilling* is an alternative disposal pathway that is being gradually phased out.

The results from monetary mapping acknowledge the findings from Weckend et al. (2016) that society, consumers and producers carry out downstream activities like waste collection, transport, treatment and disposal. The government agencies regulate the overall management and use taxes to support the operations financially. Some differences can be observed when comparing the findings since Weckend et al. (2016) are based globally, while this study concerns the EU level. For example, since most producers in the EU countries are subscribed to a producer responsibility agency, the burden on the consumer for proper disposal is reduced.

EPR makes it possible to create funds for financing of the downstream activities, and the added costs are passed to consumers in the form of higher prices. The final market price of modules depends on their preparation costs, which vary significantly depending on different cases.

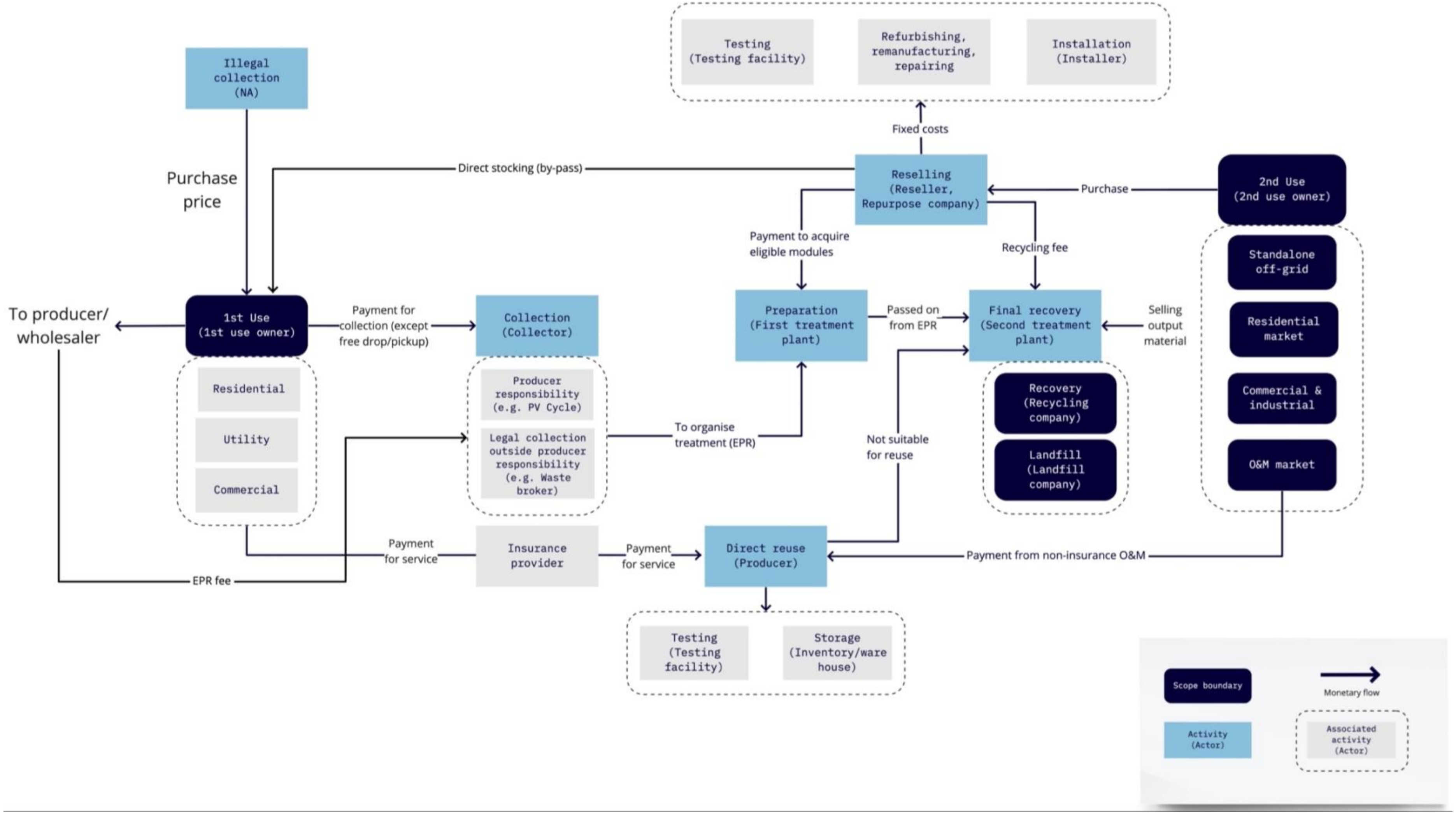

Figure 19. Monetary flow mapping (author's elaboration)

5. Discussions, limitations, and recommendations

The objective of this research is to investigate the different pathways which second life solar PV follow in the EU region. Regarding the objective, three research questions are posed, of which findings for the first two are stated in Chapter 4. This chapter presents and discusses the implications of overall findings and answers to the final sub-question 3: ***RQ3: What are the major drivers and bottlenecks in developing a successful second life market for PV modules?***

To nuance these findings, the limitations of the study in terms of the adopted methodology and practical limitations are presented. Based on the overall findings, three recommendations that can be given to the industry and policy makers are outlined.

5.1 Drivers and barriers for second life usage

The presented findings consist of a discussion based on the interpretation of overall results. The discussion is grouped in five dimensions which were deduced from the collected data using thematic analysis.

5.1.1 Financial aspects

The financial aspects regarding the demand and supply sides are an essential factor driving the second life market activities. Recent work from Nussholz et al. (2020) and Kaddoura et al. (2019) support the results from monetary mapping that costs are still a major concern for firms, with labour being an item of significant cost. This section is divided into supply and demand side to understand the market dynamics. The demand side is represented by the second life PV owners aiming to install PV modules, while the supply side by parties offering the second life PV modules in the market. To achieve a successful business case, both sides should achieve the intended financial incentives. One metric to understand them is through comparing LCOE of new and second life PV systems of the same power capacity.

It should be financially more attractive for the demand side to install second life modules over the new ones. In terms of LCOE, the decision from the end-user will depend on whether the LCOE of the second life PV system is lower than (or the same as) the LCOE of a new one. Given that the second life modules are older and with some extent of performance degradation, it is evident that the market selling prices of second life PV modules are expected to be lower than the new modules. The current market rates suggest a price reduction of 50-75% for the second life modules. Furthermore, the willingness to pay from the side of an end-user is lower because the modules have lower power density. The lower power density also increases the required installation area for the same system capacity. As a result, it also increases the associated costs of the components, which depend on the surface area of system installation, for example, cables and mounting structure.

Regarding the supply side for second life modules, it should be financially attractive to introduce decommissioned PV modules in the second life market instead of recycling or landfilling. In other words, the profits gained by the seller of second life modules should be higher than the cost for recycling or landfilling. The costs associated with introducing the modules into the second life market accumulate as new logistic activities are required in the second life supply chain. The cost of preparation for second life PV modules is not well understood because additional logistics are required. These cost ranges depend on specific cases, and it is not sure whether they are consistently higher or lower than sending the modules directly for final treatment. The main reason driving these preparation costs are the underlying condition of modules and the reverse logistics, of which economies of scale determine the latter.

Companies willing to organise second life (reuse or repurpose) activities deal with small volumes, and hence, find the preparation process for second life a financial obstacle rather than a technical one. Therefore, it is important that there should be a financially viable business case for each of the actors involved in the second life activity. For circular business models such as providing energy services, Svatikova et al. (2016) report lack of public and private financing as one of the main barriers in their policy brief report. Furthermore, there is a hesitancy for the commercial investor to support second life activities as the perspective on the rate of return is not sufficiently clear.

Recyclers also require extra financial input from the producer to drive the overall recycling process since selling output as a secondary raw material does not make a profitable business case. In future, it might be possible that recycling can become a financially self-sufficient option when the market prices of the relevant raw materials increase. In some specific cases, the recycling companies also organise collection and preparation to extend and diversify operations. Furthermore, the operational lifetime of PV modules as a product is longer compared to conventional electronics equipment. Such a long term operation makes the recycling process less attractive from the perspective of a recycling facility. However, classic waste management companies usually resort to only recycling due to limited resources and a lack of a business case for testing and selling the functional modules. These prices depend on the demand and supply ratio in the market. If the recycling companies intend to sell still functional modules in the second life market, the economics would be further determined. Similarly, for second life modules, the increasing volumes projected for the future years will inundate the market with supply options. If the demand does not match the supply, the market will witness oversupply. The increase in the supply of second life modules would also mean that companies will be able to harness the benefits of economies of scale in the preparation stage, which will lower operational costs.

5.1.2 Regulations

The present opportunities in second life market are limited due to lack of availability of modules, which is expected to change with time. Although the regulations for EoL treatment are set to guide the management of the waste modules, there are no clear directives in place for second life modules. Undefined roles of responsibility in this case leads to different second life pathways including the ones that are illegal resulting in material and financial leakages from the system (see box 1). The factors affecting the economics of the second life modules market can also become clear when standards are enforced to confirm which modules qualify for second life and which ones do not. Lack of clear guidelines and a regulatory framework also inhibit some companies from entering the market due to risks of policy changes. Certifications like cradle to cradle also encourage the end users to implement second life modules, thereby increasing their demand.

Lack of clarity in existing regulations also restricts some actors to organise their business activities. It might be possible that there exist a conflict for the new business models operating on second life applications with the conventional business models for first life. On the other hand, the actors using the existing legislations operate at the edge of legality. For example, in the EU Waste Framework Directive 2008/98/EC, the definition of "fully functional" applied to a PV module remains unclear since the functionality of the PV module can vary depending on different levels of performance.

Recycling is the last step in the circular economy but the current recycling technologies at mainstream scale are not fully equipped to valorise the important metals present in very low quantities. Some of these are even classified as critical raw materials. The market prices for the secondary raw materials can provide an incentive for the recycling industry to adopt more rigorous resource valorisation methods. Combined with unclear criteria for second life, limited incentive for treating the PV modules often result in the modules sent outside the EU. Cases of selling second-hand PV modules with low quality to overseas reflect badly on the reuse market as well. Most typically, these countries lack the regulations and controls for electronic waste too, leading to poor disposal.

5.1.3 Market acceptance

Market acceptance of second life modules is central to their uptake in the market. Different market segments have their demands. The aesthetics of the modules are important for residential customers, mainly because the roofs are tilted, and the modules are visible, unlike on flat rooftops. The metrics such as LCOE can be used to evaluate the financial viability of old and new modules. However, other *real-life* factors like aesthetics and profitability over the lifetime are also important. For residential households, the main objective for installation is to generate electricity for self-consumption, but aesthetics also play a role since the rooftops are sloped. If the surface area for installation is limited, the use of second life modules become less attractive. The decision for installation will likely concern aesthetics in addition to the primary LCOE. Hence, it can be assumed that applications where aesthetics are less important such as flat roof or stand-alone off-grid, are more suitable markets for second life modules.

The behavioural aspects like the perception of second life modules being old, inferior to new ones and not worth investing in also affect the customer choices. Additionally, new modules come with warranty coverage which can incite the user to prefer new modules over second-hand ones even when the functionality is met by the latter. In one of the interviews, it was observed that the price-conscious customer prioritizes the price of the second life modules over their warranty coverage.

Repairing of high-valued components like inverters is well established in different PV market segments. Conversely, the repair of defective modules is often not viable in financial terms under the current market conditions. The continued reductions in the price of new PV modules are also important factors that affect the repair and refurbishment market. Despite these factors, there still exist some niche markets presently for second-hand modules. One of them is in the O&M market when a specific module type is in high demand to replace a defect module of the same type but not manufactured anymore. End users with a preference for a similar-looking PV module often rely on older modules for replacement, as aesthetics play an important role in their case. In the event of replacing a single panel in string following weather damage, older modules are preferred over the new ones. Similarly, for technical reasons like matching the power output of the system and policy reasons regarding feed-in tariff agreement, the second life modules can be of particular interest.

5.1.4 Operational aspect

Technically, the average operational lifetime of a solar PV module is between 25-30 years with an yearly degradation rate. If the decommissioned modules are to be introduced into a second life, it is essential to understand the degree to which this second life is relevant and feasible. It is, however, very context and case dependent. Given the remaining technical lifetimes of the decommissioned modules, circular economy principles like maintenance and repair are used by the actors to utilise the modules to their maximum operational lifetime. For the commercial and utility scale PV, the preventive maintenance and systematic monitoring services are common. However, these kinds of contracts are much less widespread in the residential market. Despite their promise to deliver result-oriented elements such as performance-based reimbursements, guaranteed response times and so on, these service contracts face less favourable economic conditions in the residential markets (Dodd & Espinosa, 2018).

The internal CIRCUSOL research has shown that the introduction of modules into second life proves to be more competitive than recycling, not only in terms of finances but also environmentally. The environmental impacts can be decreased by adopting second life modules for operation rather than sending them to recycle or landfill. The technical aspects which make second life interesting in the environmental terms are age of the module and impact of the logistics till second life application. There are a few trade-offs like age of modules, transportation and level of intervention required in terms of repair when recycling can be considered as a better option for functional modules than integrating them in a second life market. For relatively younger modules around the age of 10 years with little to no defects, the second life case is likely to be attractive. If the modules are very close to their end of technical life, the extension of service lifetime might not be interesting environmentally. However, additional insights are required in terms of how change in geographical location, hence, the irradiation which may increase the output yields can impact the decision.

Moreover, the volumes of second life modules are low currently but will grow as the installed modules reach their end of life. It is still not clear that with economies of scale, how will the responsibilities and benefits for second life activities be distributed. Even with an established take-back system in the current situation, the responsibilities and opportunities for second life activity through private companies are less understood. One possible reason can be that there is little to no communication between private companies and manufacturers. Accurate data on the PV systems failure is still work-in-progress due to low volume of decommissioned modules. If the information does not exchange between the actors, the cooperation opportunities can become scarce, thus, slowing down the second life possibilities and resulting in less nuanced decision making.

5.2 Recommendations for further activities

Based on overall study results, the following recommendations are presented in this section.

5.2.1 Improving regulations for second life (reuse and repurpose) activities

Introducing reuse directives, including technical guidelines and recommendations for quality control of second life PV modules, can improve the confidence among the market actors. Stahel (2019) also highlights the role of governing bodies in assisting the private sector to transition to a circular economy. Technical guidelines on the EoL sorting, testing and labelling of the PV modules based on quality criteria will likely decrease the proportion of functional PV modules ending in the recycling process. The current figures of PV waste volume encompass both functional and non-functional modules, including the ones with manufacturer defect, damaged due to weather conditions, and replaced with a newer model. Moreover, the preparation costs for second life vary significantly depending on the type and scale of tests, level of automation and the local labour costs. In order to draw reliable conclusions for these costs, development of standards for preparation process and certification is necessary. Standards such as certification for selling second life PV modules can be an appealing option to offset the cost of recycling.

The preparation for final treatment activity is the key to unlock circular economy in the photovoltaic supply chain. These can officially become circular economy centres which can develop optimised handling and preparation of EoL PV modules. It is likely that such activities will generate jobs for skilled workers at these circular economy centres. Decommissioning on site is also likely to create additional jobs in the downstream PV industry and is expected to grow. Similarly, the jobs for skilled workers in preparing the modules for second life and repairing them will increase. These specialised jobs will enable the actors enabling second life of PV modules to provide uninterrupted services in the market. The collaboration between different actors can create skilled jobs at both on-site and in circular economy centres. However, the inclusion of factors like automation could also bring down the potential number of jobs. It should be noted that the potential for job creation also depends upon the involvement of member states and the solar power sector. A correct estimate is not yet available, hence, further research is recommended to understand the potential of job creation with introduction of new regulations for second life activities.

5.2.2 Collaboration between actors for financial benefits

In the current situation, the actors in the supply chain of second life PV modules can benefit from the higher prices for functionality over selling individual raw materials from the recycling process. The mapping of information exchanges along the supply chain revealed limited information exchanges between private companies and manufacture, making it difficult for the circular strategies to flourish. Along with developing better recycling processes, the industry should explore reusing and repurposing the PV modules whenever possible since these are likely to fetch higher prices than the raw materials inside them. Collaboration is a key in unlocking these benefits through creating transparency along the supply chain, optimised reverse logistics and testing facilities for lower costs for preparation of modules for a second life or even recycling. These findings also align with the recent research stressing that the collaboration between firms is an essential part for developing circular business models (Bocken et al., 2018) (Brown et al., 2019). After the first use, the reverse logistics and preparation of PV modules are perhaps the most dominant factors affecting the costs of modules in the second life market. The reverse logistics for PV modules eligible for second life requires careful handling and inspection processes that require skilled workers.

For example, a cross-collaboration between actors such as companies organising preparation (testing) and second life (reselling/repurpose) can effectively lower the costs of handling and processing the incoming modules after first use. The preparation process before final treatment is like the process for preparation before second life. The waste management companies handling large volumes of PV modules can offer preparation services to the smaller companies willing to resell and repurpose products in the market. Such an exchange of services can allow the waste management company to offer intake of larger volumes of decommissioned PV modules, create on-site testing for reducing the costs and sell them to a partner to avoid recycling. At the same time, the partner company offering second life modules can benefit from lowering the costs of capital expenditure as the testing can be outsourced and conducted in large numbers.

Currently, the market value of used PV modules remains unclear as new modules are becoming available at declining costs, and pilot-scale technologies are emerging for mass production. The increased collaboration between the actors in the supply chain can enable prediction mechanisms for enhancing the reverse logistics, optimising the supply chain in general and using the information to validate new business models. Even for recycling, an active collaboration with entities using recycled materials can further support the market fit for new recycling technologies. Access to the details about different kind of modules like their dimension and material composition can likely benefit the recycling companies to optimise their process and plan the selling of recycled material. This will be possible when actors start forming mutually beneficial partnerships and sharing information, which is a big challenge. To overcome these challenges, improved data collection mechanisms are required, currently limited by the fragmented nature of the market and the relatively long operational lifetime of PV systems.

5.2.3 Promoting second life perception

The conventional social perception of second-hand modules, like any second-hand product, makes it less desirable among the mainstream customers. Customers perceive refurbished products as exhibiting inferior performance. It is important to overcome this barrier to create a desirability in the market for different applications, especially as the good quality functional modules are becoming more available with time. The quality of the second life PV modules and their financial value are central to create a desirable perception in the market. The quality of these modules cannot be augmented slightly but the improvement in product description can create transparency and confidence in the product. Information of the product such as technical specifications, insurance, clear images, and reputation of the vendor can create confidence in the second life modules put in the market. Most of these factors are taken into account by warranty, which has a central role in creating a positive perception of second life modules. The repurposed products can be described with clear description on how they create value and quote the price based on it. For the same reason, a technical standard with product quality requirements should be developed as a part of the improving the regulations for second life and repair activities.

The second factor central to create a market desirability for second life PV modules is their financial value. Unlike other forms of energy production which have ongoing operational costs, majority of the costs for PV systems is required to be paid at the beginning of installation phase. Reducing these initial capital costs is central to gaining the interests of a price conscious customer. Finding a market fit for second life PV modules can enable the larger goal of deployment of distributed renewable energy generation without significant upfront investments required from the end user. A balance of keeping the prices low while creating confidence through transparency can promote positive perception of the PV modules for second life. LCOE can serve as a metric to determine the financial viability of the installations, since it can also be applied in specific use cases related to self-consumption. Standardized pricing based on the quality requirements met by the second life modules along with a warranty is recommended in this case. In addition, the demonstration projects (e.g., CIRCUSOL) installing second life modules, testing energy-as-a-service business models, reselling the modules for second life and even repurposing them to create niche market products should be explored to create reliable source of financial knowledge.

For the customers who do not gain confidence with the current business models, service-based models (EaaS) for second life modules can be a new niche to be explored. In these models, the customer is given assurance of the energy output results instead of having a product focus (IRENA, 2020). The ownership of the product can stay with the service provider who uses functional second life modules sourced at relatively lower prices. These models can offer several energy-related services rather than only supplying electricity. A study by IRENA (2020) acknowledged that energy service providers support deployment of PV systems and result in better demand-side management. For example, they can support consumers willing to switch to self-consumption by installing second life PV systems on their rooftop coupled with battery storage. Even for end-users who cannot or would not prefer to install distributed energy in their residencies, a range of innovative energy services are emerging (IRENA, 2020). In this scenario, the reverse logistics and preparation for second life will play an important role in determining the costs, along with the remaining functionality of second life modules. Moreover, the market acceptance and business viability for these service-based models remain to be further tested.

5.3 Limitations of the study

In terms of circular strategies (Bocken et al., 2016), the focus of this study places an emphasis on slowing the material loops, rather than narrowing or even closing the resource loops. The scope is geographically limited to Europe in terms of technology and market for PV modules. In terms of the methodology, qualitative research methods were thought to be well suited and applied to the study which also have their own limitations. The main limitation is that the results of the study are less tangible. The primary data collected from the interviews was limited mainly to the consortium members of the CIRCUSOL project and geographically to Belgium, Germany, and one interviewee from Lithuania. However, it was attempted to establish contact with experts outside of the project and interviews were organised as well. The number of interviews were also limited due to time limitations, which might lead to a less nuanced perspective. Since the interviewees were already aware of circular economy concepts and some were a part of the CIRCUSOL project, it is possible that the results contain a positive bias towards the second life use. The limitations of the method selected for data analysis along with a bias from the researcher in terms of data interpretation applies as well. Geographically, it is likely that the limited information collected from the interviews lead to generalization of the findings for the entire European region. In terms of the temporality, the study captures a snapshot of the situation, the market is evolving as more modules are getting decommissioned. The market dynamics should change with time as new developments in terms of regulations and business applications are being developed and proposed. Besides, the market dynamics in informal activities such as illegal collection and disposal of PV modules is not represented in the study due to practical limitations.

6. Conclusion

In this chapter, the answers to the three research questions framed in the introduction chapter are combined to conclude an answer to the main research question: ***How can supply chain of second life photovoltaic be developed within EU to achieve circular economy goals?*** Furthermore, the implications of the study are discussed. Based on the conclusion, a number of suggestions that can be given to the researcher for future work in this direction are presented. In this research, the supply chain of second life PV modules was studied with literature review and interviewing the experts to collect the primary data. Using the collected information, supply chain maps were developed to explore main flows created by different activities in the European context. The result outcomes were illustrated using three sets of flows: "material flow" in which the exchanges of PV modules were explained, "information flow" in which the information exchanges supporting the material flow were studied and lastly, the "monetary flow" in which the financial exchanges created between different activities were mapped. With these three mappings, the relationships between the activities and actors in the supply chain of second life PV modules were analysed. The results were interpreted to identify and nuance the key opportunities and barriers for market development and recommendations for policy makers and the private sector were put forward.

The thesis confirms that *the functional PV modules after their first use can manifest into second life either in the same format or as a different product (or service).* For the former case, modules are sold directly for reuse but might also involve some interventions like repair or refurbishment before selling. The latter case is less observed, where the modules are repurposed into a new product or service, and typically attains a niche application e.g., urban mobility and events. In Europe, the WEEE legislation sets the guideline for regulating activities concerning the EoL PV modules (European Parliament, 2012). However, the member countries are free to transform these rules to integrate into their national context which complicates the overall generalisation of supply chain in the EU scale.

A number of results also assist with identifying the factors influencing the *preparation success rate.* These factors should be taken into account the different activities along the supply chain since they influencing the prices and success of PV modules entering the second life activities. Material flow mapping suggests that the point of collection in the reverse logistics and handling of PV modules play the most crucial role in augmenting the preparation success rate. The reserve logistics or take-back collection system differs in each member country and improper handling of PV modules can lead to damages such as microcracks. From an information and monetary point of view, the prevailing conditions of PV modules and market use requirements also have a direct effect on this success rate. Hence, it is reported that the past performance and future use applications of the PV modules are also key considerations to determine their success in the second life market.

The thesis results suggests that *currently, there are limited opportunities for introducing functional PV modules into a second life to extend their lifetime.* Even with a vivid and growing interest regarding circular economy practices in this sector, there exist a multitude of barriers slowing the implementation. These include a bundle of economy, policy, market, and technical barriers. The lack of profitability for the supply side is a major bottleneck, followed by absence of regulatory incentives and inadequately developed infrastructures for collection and preparation for second life. From the demand side, market acceptance is central to the success of the second life market. At the same time, it is important to note that this study provides a snapshot of the second life PV market and the market is evolving rapidly. With these elements in attention, three recommendations for further activities are prepared. Firstly, improving the regulations for second life activities to improve confidence within the actors operating in the supply chain. Next, collaboration between actors in the supply chain like the exchange of services to provide mutual benefits and lower the overall preparation costs for second life PV modules. Lastly, promoting the use of second life PV modules and reaching to new customers with innovative business modules unlocking niche product and service creation.

Lastly, this thesis study *suggests that the continued growth of the solar PV sector will evoke new challenges related to sustainability, specifically regarding the material criticality and the management of EoL products*. The global investments in low carbon energy technologies are soaring, and the already existing solar PV sector will create a huge inflow of decommissioned PV modules in Europe and globally. At the level of business models, the majority of the current ones in the sector rely on linear economy logic, which can undermine its full sustainability potential. It is highly likely that exploring circular economy actions beyond the current practices in the photovoltaic sector can potentially reduce the specific material footprint per kWh of solar electricity produced. Hence, further research should be conducted in analysing the potential of implementing circular actions in the PV industry. For example, analysing the trajectories of the firms and projects which implement circular goals like extending the operational lifetime of the PV modules. This can be complemented by creating a business case dataset to identify the possible market opportunities for the second life PVs. Based on this analysis, the goal can be to find evidence on which internal and external driving factors, market and systemic conditions have the most impact on the development and growth of second life PVs and which factors show no effect at all.

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Appendix A: Interview questionnaire

Note: The following questions show an excerpt taken from an interview with a recycling company in Germany, hence, the questions are specific to the information which was required and guided according to the responses they received.

- Aim of the thesis and visualized supply chain is explained. Would I put your company X as a recycler?
- After a panel is dismounted, who collects it and how does it reach you?
- What happens when you receive them? Who pays for them? Do you get money to collect panels, or you pay them?
- What are the parameters for deciding whether the module is eligible for a 2nd use?
- What do your purchaser parties buying 2nd life modules look for?
- What happens with the remaining modules which do not go to 2nd use?
- What volumes roughly are these streams you receive?
- How can you group the sources and quality of panels?
- There must a larger flow than what you get. So, are there more companies or waste is going outside Germany?
- For you, what is the motivation for selling to reuse? Is it more interesting to reuse than recycling? What about financial point of view?
- Where do these reuse modules you sell end up in their application?

Appendix B: List of interviewee details

Contact	Organization	Relevance in the study
Ismaël Ben-Al-Lal	Futech (Belgium)	Mr. Ben-Al-Lal has an extensive network and a good view of the current PV market. As the leader of an installer in Europe, they provided information on their inventory and testing facility for second life PVs in the context of operation and maintenance applications.
Tadas Radavičius	SoliTek (Lithuania)	Mr. Radavičius works at SoliTek alongside PhD and completed master's thesis on innovative strategies for solar industries in Europe. In addition, they provided evidence on how certifications can lead to circular business activities.
Jan Clyncke	PV Cycle (Belgium)	Mr. Clyncke has a lot of expertise in the current management of PV waste and related legislation in Belgium and France. As an expert in the field, they provided first-hand knowledge of the waste management situation in Belgium and western Europe in general.
Antoine Driancourt	Veolia (Germany)	Mr. Driancourt represents Veolia's operation in Germany related to PV waste management (recycling). They provided essential insights on the German logistics system of PV waste management.
Wolfram Palitzsch	LuxChemtech (Germany)	Dr. Palitzsch has expertise in recycling operations and sourcing waste PV modules in Germany. They provided information on their business activity such as sourcing PVs for recycling, different types of recycling and on selling second-hand modules for different applications.
Lisa Wendzich	SunCrafter (Germany)	Ms. Wendzich is the co-founder of Suncrafter and has completed their master thesis on the rehabilitation of 2nd life PV. In addition, they provided a lot of information on sourcing, funding, and off-grid application for second-hand modules in Germany.
Stefan Wippich	SecondSol (Germany)	Mr. Wippich is the co-founder of SecondSol and has an excellent knowledge of the second life PV market activities and their critical barriers.