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Moving towards a circular photovoltaic economy in Europe

A system approach of the status, drivers, barriers, key policies and opportunities

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Abstract

With the projection of a growing amount of waste from photovoltaic (PV) panels in coming years, experts and researchers have highlighted the importance of the circular economy approach to face this challenge. With this approach, risks linked to the composition of PV panels, such as pollution and wastage of valuable materials, can be reduced. Therefore, this thesis aims to provide a systematic view of the PV sector's circularity activities in Europe, analyzing the context and current situation about eco-design, reuse and recycling initiatives regarding PV panels. Also, the goal is to identify the drivers and barriers to the transition towards a circular photovoltaic sector and key policy issues, goals, and opportunities to make it more circular. The Technological Innovation System (TIS) framework was used to guide the collection, analysis and presentation of data. The analysis of the emerging European Circular PV Innovation System (TIS) is based on an in-depth literature review, interviews with 12 representatives from the solar industry and government, and participation in three webinars. Firstly, the findings indicate that circularity activities exist in the PV sector in Europe. However, the European Circular PV Innovation System is so far only in its formative phase. Among the seven functions of the framework analysed (knowledge development, market formation, resource mobilization, entrepreneurial experimentation, development of external economies, influence on the direction of search and legitimation), the knowledge development one presents a high level of strength. In contrast, the market formation for reused and ecodesigned PV panels and recycled materials is the one that needs the most improvement. Secondly, the barriers blocking the solar sector to become more circular are identified, such as lack of supply guarantee due to the low quantity of waste, low market demand and lack of specific targets in legislation. Thirdly, recommendations are provided to policymakers on improving the European Circular PV Innovation System, such as financial incentives, standards and improvement in legislation.

Keywords: Circular economy; photovoltaic panels waste, reuse; recycle, ecodesign, TIS.

Executive Summary

Background and problem definition

Among renewable energy sources, solar energy has been gaining ground, especially during the last decade, representing the third-largest renewable electricity technology worldwide (IEA, 2020). By 2022, cumulative installed capacity is expected to overtake 1 TW (Tsanakas et al., 2019) and, by 2030, reach up to 12 TW (ISE Fraunhofer, 2020b). Some factors contributing to the growth of solar systems are the reduction of the solar panel's price and international and regional goals and policies to fight climate change, such as the Paris Agreement and the Sustainable Development Goals (European Commission, 2019).

However, the growth in PV poses environmental and economic challenges. According to IRENA (2016), around 78 million metric tons of PV panel waste will cumulatively have been generated worldwide by 2050. Out of this amount, it is foreseen that about 11 million tons will be generated in Europe. The problem becomes even more significant because of the composition of PV panels, which contain hazardous materials (cadmium and lead) and rare substances (indium, gallium, silicon and silver) (Maani et al., 2020). Hazardous materials can cause risks to human health and wildlife when leached to the environment, whereas the discarding of rare and valuable substances results in the loss of valuable resources. The latter risk becomes even more critical in Europe since the continent has a high dependency on importing valuable raw materials and PV panels from China (European Commission, 2020a; Rabe et al., 2017).

To address this issue, Europe has created some policies, such as the EU WEEE Directive. This legislation considers PV panel waste as electronic waste and makes producers, distributors and importers responsible for its collection and treatment (DIRECTIVE 2012/19/EU, 2012). Due to this Directive, initiatives have been carried out by companies and other actors to face this challenge, mainly focusing on the recycling and reuse of PV panels. In addition, the EU Commission (EC) has supported projects focused on solutions to the circular economy in the PV sector through funding programs. Furthermore, the EC recently launched a study to evaluate the feasibility of ecodesign requirements for this product category, concluding that there is momentum to establish such requirements (European Commission, 2020b). The EC is currently discussing the creating of policies such as ecodesign legislation and energy label.

Despite the initiatives mentioned above, there are many obstacles to overcome, mainly related to the fact that PV panel waste has not been seen as a problem yet because of the low quantity of waste being generated nowadays. However, as shown by IRENA projections, society will have to deal with a large volume of end-of-life PV panels in less than ten years from now.

Therefore, circular economy (CE) principles, that state that materials should be used as long as possible and waste should be reduced (Ellen MacArthur Foundation, n.d.), can be one solution to this challenge. The CE approach can help society to correctly manage PV panel waste through reuse and recycling initiatives and to avoid it through ecodesign actions, thereby reducing the risks and concerns mentioned previously. Furthermore, the transition to a circular economy in the solar sector would align with the EC's New Circular Economic Action Plan launched in 2020.

The literature review showed that most of the research on the circular economy in the PV sector has focused on topics such as (i) the problem of PV waste, (ii) recycling technologies, (iii) life-cycle assessment and (iv) feasibility and economic costs of recycling and reuse. Also, regarding circular economy strategies, most attention has been given to recycling, with much less research on reuse (Tsanakas et al., 2019) and even less on ecodesign. A system approach of the status of the sector's circularity activities in Europe, with a clear picture of elements such as actors, market, strategies, policies, and investments, is lacking. Such an overview can help to understand better the current circularity activities of the PV sector in Europe. Based on an enhanced understanding of the drivers and barriers towards a circular photovoltaic economy, policymakers and companies can take action to make this transition happen.

Aim and research questions

This thesis aims to contribute to the discussion of the circular economy in the PV sector by providing a systematic view of the sector's circularity in Europe, analyzing the context and current situation about ecodesign, reuse and recycling initiatives regarding PV panels. Also, the barriers and drivers to the transition towards a circular photovoltaic sector are identified, and key policy issues, goals and opportunities are pointed out. The intention is that this systematic analysis can contribute, ultimately, to increase the level of circularity in the PV sector, making the PV technology truly renewable and sustainable through (i) the promotion of ecodesign, reuse and recycling strategies, (ii) improvement of policies and (iii) increase of investments in projects, experiments and new entrants.
The research questions that guided this research are:

RQ1: What is the state of the art on the circularity of the PV sector in Europe?

RQ2: Why is the PV sector in Europe not circular yet?

RQ3: How could the PV sector in Europe become more circular?

Research design, materials and methods used

In response to achieving the aim and answering the research questions of this thesis, it was decided to use a case study approach focused on the circular PV innovation system in Europe.

Data collection is based on (i) a review of around 60 articles and reports, (ii) participation in three webinars and (iii) conduct of 12 interviews with representatives from research institutes, government, industry associations, a Horizon 2020 project consortium, as well as companies that work with recycling, reuse and ecodesign strategies in the solar power industry (see Appendix 1 and 2). The direct content analysis method was selected for data analysis, using the Technological Innovation System (TIS) framework (Bergek et al., 2008) to guide the initial codes. The TIS framework was also used to guide data collection and interviews (see Appendix 3) and present the results.

The TIS framework has six steps, which were slightly adapted to this thesis, consisting of (1) defining the TIS (object of study), (2) identifying the components of the system that influence its development and performance, that is, the actors, networks and institutions (policies, laws and culture), (3) identifying the status of seven key functions that also influence system performance and development (knowledge development, market formation, resource mobilization, entrepreneurial experimentation, development of external economies, influence on the direction of search, legitimation), (4) analyzing the functionality of the system, (5) point out barriers and drivers and (6) identifying key policy issues, goals and opportunities. Thus, it was assumed that the system studied is the European Circular PV Innovation System, having as its object the circular economy strategies of ecodesign, reuse and recycling. In addition, steps two, three and four guided the response to RQ1, step five provided answer to RQ2 and part of the RQ3, and step six assisted in responding to the other part of RQ3.

Main findings/results

The main findings of this thesis, presented by the research question, are:

(RQ1) The results indicate that circularity activities exist in the PV sector in Europe. However, the European Circular PV Innovation System is so far only in its formative phase, with many obstacles towards a more complete transition to a circular economy yet to be overcome. In general, investments in research projects and experiments are occurring through the Horizon 2020 funding program. This has helped to involve many actors through the solar value chain, to establish networks and advocacy coalitions, and to increase the knowledge base on circularity in the PV sector. However, although legislation is partially in place (with some further policies under discussion), only a few organizations are exclusively dedicated to circular PV. Also, the level of interactions and collaborations between them is relatively limited. Furthermore, the market for reused and ecodesigned PV panels and recycled materials is not very well-formed, with some uncertainties and informalities and low demand regarding recycled materials, as well as eco-designed and reused PV panels. Therefore, some functions of the innovation system are more developed than others, the Market Formation function being the one that needs most improvement.

(RQ2) The findings presented the barriers that are blocking the solar sector to become circular. Many barriers were identified, being the majority related to market development (such as lack of supply guarantee due to the low quantity of waste; low market demand; high cost of recycling, lack of specific targets in the legislation), confirming that it is the weakest function of the European Circular PV Innovation System. Some other barriers were identified related to resource mobilization (lack of long-term and circular strategic thinking; lack of collaboration) and legitimation (low awareness about the importance of the CE strategies).

(RQ3) To answer this question, the drivers, key policies, goals and opportunities were identified. About the drivers, the main aspects that lead organizations to work with CE strategies are related to the necessity to deal with the increasing generation of waste, to the possibility of recovering valuable materials, reducing costs, and finally to the consequent likelihood of becoming less dependent of the external supply chain. In order to further enable a circular transition in the PV sector, policy makers need to foremost focus on enhancing market development, resource mobilization (human resources skills) and legitimation. Finally, the opportunities and advantages of having a more circular PV sector are related to job creation, reduction of risk of pollution, and the establishment of an internal market for recovered materials, etc.

Conclusions and recommendations

The main contribution of this thesis is related to the systemic approach that was fundamental to provide a holistic view of the status of CE strategies, filling a gap in the area of study. Specifically, the analysis of the seven functions of the TIS framework as applied to the European Circular PV Innovation System allowed to identify items such as market, policies, investments, experiments and human resources, themes that previously have not received much attention in the literature on circular photovoltaics.

Thus, this thesis contributes to the discussion of the circular economy in the solar sector and, through the key policies and opportunities indicated, to improve its circularity. Finally, there is an academic contribution due to the use of the TIS framework in an innovative way in the context of circular economy in the solar sector.

Finally, to enable a transition to a circular economy by strengthening eco-design, reuse and recycling initiatives, this thesis encourages policymakers to consider different policy approaches, such as financial incentives (subsidies and green public procurement), standards, ecolabels, and specific targets on legislation, as well as awareness-raising initiatives. The thesis also recommends five areas for future research that is (i) develop updated, and more accurate projections about how and when the PV waste volume is going to grow under different scenarios, (ii) consider circular business models as the object of study, given that they are considered essential to promote the transition towards CE; (iii) compare the results of this thesis (such as resources invested, number of publications, number of organizations, barriers, etc.) to the results of other similar systems to assess the performance and development of the TIS from a different perspective, (iv) perform the same analysis of this research ten years from now and (v) investigate and study the feasibility of financial incentives to support a circular transition in the PV sector in Europe.

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Abbreviations

Ag – Silver

Al – Aluminium

$AlMg_3$ – Aluminium alloy

CdTe - cadmium telluride

CE – Circular economy

CENELEC – European Committee for Electrotechnical Standardization

CEO – Chief Executive Officer

CEU – Central European University

CIGS copper-indium-gallium-diselenide

CO_2 – Carbon dioxide

Cu - Copper

C-Si - Crystalline silicon

DG GROW - Directorate-General for the Internal Market, Industry, Entrepreneurship and SMEs

EC – European Commission

EEE – Electrical and Electronic Equipment

EOL – End-of-life

EU – European Union

EVA - ethylene vinyl acetate

GW – Gigawatt

IEA – International Energy Agency

IIIEE – The International Institute for Industrial Environmental Economics

IPCC - Intergovernmental Panel on Climate Change

IRENA - International Renewable Energy Agency

JRC – Joint Research Center

NGO – Non-governmental organization

OECD – Organization for Economic Co-operation and Development

PRO – Producer Responsibility Organization

PSS – product-service system

PV – Photovoltaic

PVF - Polyvinyl fluoride

R&D – Research and Development

Si - Silicon

TiO_2 – Titanium dioxide

TCO - transparent conducting oxide

TIS – Technological Innovation System

TW – Terawatt

Zn - Zinc

WEEE – Waste Electrical and Electronic Equipment

1 Introduction

1.1 Background and importance

Climate change is considered one of the biggest challenges that society faces nowadays, with the energy sector responsible for more than 65% of global greenhouse gas emissions (IPCC, 2020). Renewable energies are gaining prominence globally since they play a fundamental role in meeting the energy demand whilst contributing to reducing greenhouse gases. Furthermore, the deployment of renewable energies is aligned with international and regional goals and policies to fight climate change, such as the Paris Agreement, Sustainable Development Goals, and in the case of Europe, the Renewable Energy Directive and the Green Deal (European Commission, 2019).

Among renewable energy sources, solar energy has been gaining ground, especially during the last decade. Between 2010 and 2019, the compound annual growth rate of cumulative photovoltaic (PV) installations was 35% (ISE Fraunhofer, 2020a). In 2019, electricity generation from solar power increased 22% globally, resulting in a 3% PV share in the global electricity generation, with around 600 GW of total installed PV capacity, representing the third-largest renewable electricity technology (IEA, 2020). By 2022, cumulative installed capacity is expected to overtake 1 TW (Tsanakas et al., 2019) and, by 2030, reach up to 12 TW (ISE Fraunhofer, 2020b). In Europe, it is likely that in the coming years, the solar system market will grow extensively beyond several tens of GW per year (ISE Fraunhofer, 2020b; SolarPower Europe, 2020).

The increase of the solar power sector is also connected to the cost reduction of its components. In most countries, the electricity generation costs from PV systems reduced significantly, becoming economically attractive and contributing to the increase in its use in the coming years. Between 2010 and 2019, the cost of solar PV globally decreased by 82% (IRENA, 2020b).

1.1.1 Problem definition

However, the growth in PV comes with a cost. The increase in the demand for solar energy in the coming years will result in the disposal of vast amounts of waste from the PV panels. According to IRENA, around 78 million metric tons of PV panel's waste will cumulatively have been generated worldwide by 2050, as shown in Figure 1-1. Out of this amount, it is foreseen that 20 million tons will be generated in China, and around 11 million tons will be generated in Europe, with Germany at the lead, with more than 4 million tons (IRENA, 2016).

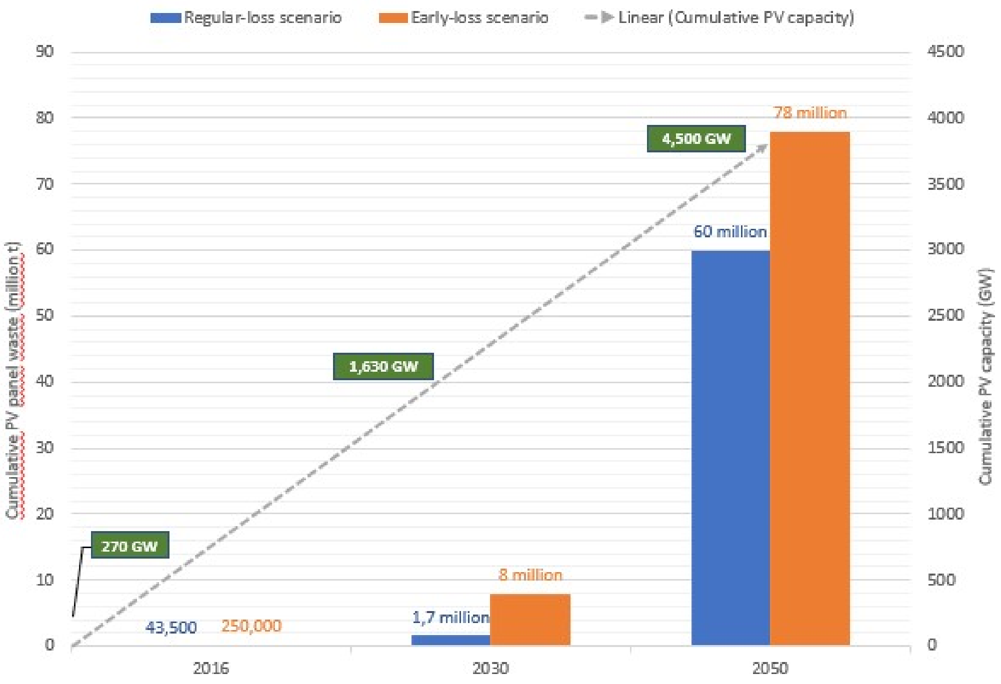

Figure 1-1 Overview of global PV panel waste projections, 2016-2050.

Source: Own representation from IRENA (2016).

The problem becomes even more significant because of the composition of PV panels, which varies according to the type of technology. In general, they contain hazardous materials and rare substances (Maani et al., 2020). Hazardous materials such as cadmium and lead can cause risks to human health and wildlife when leached to the environment. The discard of rare and valuable substances such as indium, gallium, silicon and silver results in the loss of valuable resources (Chowdhury et al., 2020; Deng et al., 2020; Farrell et al., 2020).

Considering that the practice of sending PV panels waste to landfills is still in place in many countries (Deng et al., 2020; Farrell et al., 2020), the risk of leaching can be even higher in low-income countries where the environmental legislation is not strong, and the control of pollution is not well established. In Europe, the risk of wastage of valuable substances becomes even more critical since the continent has a high dependency on importing valuable raw materials and PV panels from China (European Commission, 2020a; Rabe et al., 2017).

Therefore, environmentally adequate management of the PV panels' waste is necessary, aiming to minimize its impacts on the environment and human health and reduce the extraction of rare materials (Salim et al., 2019). Also, initiatives that consider the whole life cycle of the PV panels, including its design rather than only its end-of-life, are equally relevant since up to 80% of the product's environmental impacts are set during the design phase (COM(2020) 98 final, 2020).

1.1.2 The policy, business, and investment context

To address the issues mentioned in the previous section, some policies have been created. In Europe, the Waste Electrical and Electronic Equipment Directive (EU WEEE Directive) considers PV panel waste as electronic waste (e-waste) and makes producers, distributors and importers responsible for its collection and treatment through the Extended Producer Responsibility principle. Furthermore, the Directive encourages the producers to design the PV panels in a way that optimizes the reuse and recovery of the electrical and electronic equipment waste (DIRECTIVE 2012/19/EU, 2012).

Due to this law, initiatives have been carried out by companies and other actors to address this issue, mainly focused on the recycling and reuse of PV panels. In addition, the EU Commission has supported the creation of projects through Horizon 2020, which focus on solutions to the circular economy in the PV sector.

Another key European policy is the Directive 2009/125/EC that establishes a framework for ecodesign of energy-related products that included the PV panels in its 2016-2019 Ecodesign Working Plan (COM(2016) 773 final, 2016). Because of that, the European Commission carried out a study to evaluate the feasibility of ecodesign requirements for this product category. This study concluded that there is momentum to establish such requirements, which is particularly relevant now that discussions are taking place for resuming the production of PV panels in Europe (European Commission, 2020b).

However, there are many obstacles to overcome regarding these policies, business strategies, and investments. The challenges are mainly related to the fact that PV panel waste has not been seen as a problem yet because of the low quantity of waste being generated nowadays. However, as shown by IRENA projections, society will have to deal with a large volume of end-of-life PV panels in less than ten years from now.

1.1.3 The Circular Economy approach

The Circular Economy (CE) principles state that products/materials should be kept in use as long as possible, and waste and pollution should be designed out (Ellen MacArthur Foundation, n.d.). Therefore, the CE approach can be one solution to prepare society to correctly manage PV panel waste through reuse and recycling initiatives and to avoid it through ecodesign actions, thereby minimizing the risks and concerns mentioned above. Furthermore, moving from a linear economy to a circular economy strategy in the solar power sector would enable several opportunities and advantages to all the stakeholders involved, as is explored better throughout this thesis. It would also be in line with the New Circular Economy Action Plan, launched in 2020 by the European Commission, also explained further in this research.

Based on recent research on the circular economy in the PV sector, it is evident that most of the research has been related to the following topics: (i) the problem of PV waste (Chowdhury et al., 2020; Deng et al., 2020; Franz & Piringer, 2020; Majewski, 2021; Salim et al., 2019; Sica et al., 2018; Strupeit & Bocken, 2019; Tao et al., 2020; Tsanakas et al., 2019; Wade et al., 2017), (ii) recycling technologies (Chowdhury et al., 2020; Deng et al., 2020; Farrell et al., 2020; Heath et al., 2020; Sica et al., 2018; Tsanakas et al., 2019), (iii) life-cycle assessment (Deng et al., 2020; Heath et al., 2020; Muteri et al., 2020) and (iv) feasibility and economic costs of recycling and reuse (Deng et al., 2020; Heath et al., 2020; Majewski, 2021; Sica et al., 2018; Tao et al., 2020; Tsanakas et al., 2019; Wade et al., 2017). With regards to the circular economy strategies, most attention has been given to recycling, with much less research on reuse (Tsanakas et al., 2019) and even less on ecodesign. A system approach of the status of the sector's circularity activities in Europe, with a clear picture of elements such as actors, market, strategies, policies, and investments, is lacking. Such an overview can help to better understand the current circularity activities of the PV sector in Europe. Based on an enhanced understanding of the drivers and barriers towards a circular photovoltaic economy, policymakers and companies can take action to make this transition happen.

1.2 Aim and research questions

This thesis aims to contribute to the discussion of the circular economy in the PV sector by providing a systematic view of the sector's circularity in Europe, analyzing the context and current situation about ecodesign, reuse and recycling initiatives regarding PV panels. Further, the thesis aims to identify the barriers and drivers to the transition towards a circular photovoltaic sector, and to point out key policy issues, goals and opportunities. The intention is that this systematic analysis can contribute, ultimately, to increase the level of circularity in the PV sector, making the PV technology truly renewable and sustainable through (i) the promotion of ecodesign, reuse and recycling strategies, (ii) improvement of policies and (iii) increase of investments in projects, experiments and new entrants.

The research questions guiding this research are:

RQ1: What is the state of the art on the circularity of the PV sector in Europe?

RQ2: Why is the PV sector in Europe not circular yet?

RQ3: How could the PV sector in Europe become more circular?

The analysis will be based on the Technological Innovation System (TIS) framework, considering aspects like actors, networks, policies, standards, market and resources, among others described in section 2.2.

1.3 Scope and delimitations

The thesis focuses on Europe due to three main reasons. Firstly, the region was one of the first to install PV panels and will contribute significantly to the amount of waste generated in the coming years. Secondly, it is the only place that currently has specific regulation regarding PV panels waste management (Majewski, 2021), with targets for recovery and preparation of reuse and recycling. Thirdly, because of this legislation, Europe presents some circular economy initiatives such as recycling and reuse and possesses some investments related to specific circular economy projects in the solar sector, as mentioned in the introduction.

With regards to the policies in place, this thesis focuses on Europe-wide policy and does not investigate the national policies of EU member states individually.

Regarding the circular economy strategies performed by companies, the thesis focuses on recycling, reuse and ecodesign practices. It was decided to study the three strategies for several reasons. (i) Generally, the publications focus on specific subjects such as technology, costs and environmental impact, but there is no holistic view of each strategy contemplating these aspects and others such as market, awareness and policies. In addition, there is also no general and consolidated analysis covering the three strategies in the same document; (ii) Although the recycling strategy is the one that has been researched more extensively, in addition to the issues mentioned in the previous item, it has great relevance for the recovery of high-value materials, an important issue to Europe; (iii) The reuse strategy is more informal, has fewer incentives and information available compared to recycling. It is crucial to extend the lifetime of products and reduce the amount of waste sent to landfills; (iv) The ecodesign strategy is the one with least available information, and it is extremely important to reduce product's environmental impact and enhance its recyclability and reusability.

The scope of the thesis focuses on PV panels products and waste only. That is, it does not consider other solar electric system components, such as inverter, racking, and battery storage.

The thesis does not include social aspects, such as labour conditions, health and safety and issues relating to conflict minerals. The focus is mainly on environmental and economic factors.

1.4 Ethical considerations

The research is not supported or funded by an external organization. Therefore, there is no risk of influencing the conclusions or nature of the work.

The interviews occurred on a voluntary basis, i.e., all the participants agreed to be interviewed. They were also asked to sign a consent form agreeing on having the interview audio-recorded and its content transcribed, analyzed and published, respecting the confidentiality of their names. Information gathered from interviews was safely stored and erased after the thesis period.

There is no potential for the research results to be harmful to the subjects' reputation, dignity, or privacy.

Lastly, the research design has been reviewed against the criteria for research requiring an ethics board review at Lund University, and it has been found to not require a statement from the ethics committee.

1.5 Audience

This research can help companies that want to engage with circular economy initiatives in the solar sector or improve the actions in place through the understanding of policies, investments, actors and drivers and barriers. With that, companies can take steps that help the transition to a circular economy, such as mobilization of resource, engagement with actors, participation in advocacy coalitions, among others.

It can also help policymakers by firstly providing a better understanding of the problem of PV panel waste, the current situation and its deficiencies. Secondly, it provides important information to prepare for a better scenario by taking action in advance, such as the creation or improvement of policies. The results of this research may also be interesting for developing countries that are increasingly looking for renewable energies to compose their energy matrix and will face the same problems related to PV panel waste in the near future. In the case of Brazil, I have a personal interest in transferring the results of this research to my home country, helping somehow to add knowledge about sustainable practices regarding the PV panels waste aligned with the increasing use of solar power.

Finally, this research can also help scholars to understand better the applicability of the TIS framework to the circular economy context.

1.6 Structure of the thesis

This research is structured and organized as follows:

Chapter 1: introduces the subject of the thesis presenting its background and explaining its importance. It also presents the problem that is addressed by the author, as well as the aim of the thesis and the three research questions. The chapter also states the scope, ethical considerations and audience of the thesis.

Chapter 2: provides an overview of the PV sector about the technology types, the environmental impact of the PV waste and the circular economy perspectives and strategies (ecodesign, reuse and recycling). It also presents the tools and frameworks to assess the circular economy and introduces the technological innovation system (TIS) framework.

Chapter 3: outlines the research design, materials and methods used in the thesis regarding the collection and analysis of data. It also explains how the author applied the TIS framework to the research to answer the three research questions. At last, the methods to ensure the validity of the thesis were presented.

Chapter 4: presents the main findings and results of the thesis, based on the data obtained from interviews, webinars and additional literature. The information is given based on the components and functions of the TIS framework.

Chapter 5: discusses the findings of the thesis, interpreting the results. In addition, it shows the importance of the thesis through its contributions. It also provides general reflections about the legitimacy and generalizability of the findings, as well as about the limitations of the research.

Chapter 6: summarizes the main findings of each research question and presents recommendations for policymakers and future research.

2 Literature Review

This chapter will present an overview of the PV technology types, the environmental impacts regarding its waste, the circular economy approach to address the issue, and the circular economy strategies carried out in Europe regarding this sector.

Also, a literature review regarding tools and frameworks to measure circular economy status and performance was conducted. It is also presented the Technology Innovation System (TIS) framework used in this research to guide the data collection, interviews and presentation of results.

2.1 The PV technology types and the importance of waste management to avoid risks

The main component of a photovoltaic panel responsible for converting the solar radiation directly into current electricity is the solar cell, made of semiconductors materials. In the 19th century, it was observed for the first time that sunlight could generate electrical energy, and around 1950 the first solar cell was developed. From that period to the present, the technology of solar cells evolved significantly and continues to evolve, which makes it challenging to define the precise composition of the solar PV panels (European Commission, 2020a). However, they are mainly divided into three groups, called Generation, and present some general characteristics, as shown in Table 2-1:

Table 2-1 Photovoltaic technologies, description, components and share in the market.

Generation type	**Technology Types**	**General description and components**	**Share of production in the market**
1st Generation: Silicon-based (c-Si)	- Monocrystalline - Poly- or multicrystalline - a-Si (amorph/micromorph)	The oldest and most commonly used technology. It currently has the best efficiency of commercially produced cell technology. Components of a typical c-SI panel: glass, polymer, aluminium (more than 90%), silicon (around 5%) and the rest is lead (Pb), copper, silver and tin.	95% in 2019, being the monocrystalline responsible for 66%.
2nd Generation: thin-film based	- Copper indium gallium (di)selenide (CIGS) - Cadmium telluride (CdTe)	Components of a typical thin-film panel: glass, aluminium and polymer (more than 90%) and other materials including cadmium, selenium,	5% in 2019, being the CdTe more representative.

		indium, copper, zinc, tellurium, gallium.	
3rd Generation	- Concentrating solar PV (CPV) - Organic PV/dye-sensitised cells (OPV) - Crystalline silicon (advanced c-Si) - CIGS alternatives, heavy metals (e.g., perovskite), advanced III-V	The majority are not yet commercial and are still being tested. No information about the composition was analyzed.	Not applicable.

Source: Based on IRENA (2016), ISE - Fraunhofer (2020a) and author research

Figure 2-1 shows the typical structure of both C-si (first generation) and CdTe (second generation) PV panels with the percentage mass composition:

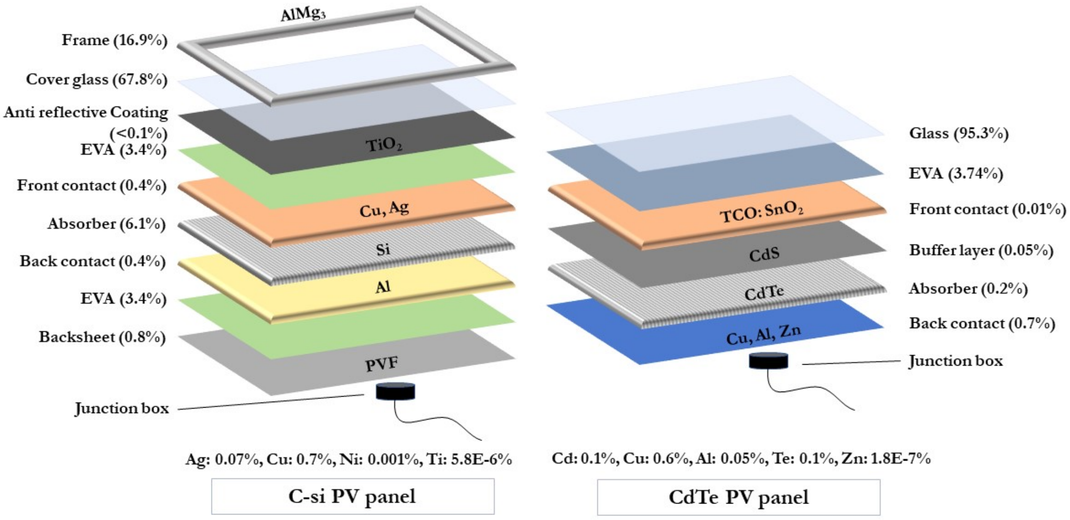

Figure 2-1 – Structure and percentage mass composition of both C-si and CdTe PV panels.

Source: Based on Maani et al. (2020)

Due to some hazardous and rare materials in the solar PV panels, as noticed in Table 1-1 and Figure 2-1, the proper management of its waste is necessary to avoid environmental impacts on water systems, soil, wildlife, and human health. Currently, the common practice worldwide is to store or send the PV panels to landfills when it reaches their end of life after around 25 to 30 years (Deng et al., 2020; Farrell et al., 2020). Only about 10% of them are recycled worldwide (Farrell et al., 2020).

Also, adequate management of the PV panel waste can recover the valuable metals contained in PVs. According to IRENA (2016), the 78 million tons of PV panels waste predicted to be generated by 2050 could be worth around 15 billion dollars on global commodity markets if properly recycled.

The importance of recovering the valuable materials of the PV panels can be even more relevant to Europe that has a high dependency on the importation of raw materials, mainly the metal ores and minerals that are found in the PV panels and other electrical and electronic equipment – EEE (European Commission, 2020a; Rabe et al., 2017). Also, most of the PV modules consumed worldwide are currently manufactured in China (ISE Fraunhofer, 2020a). Therefore, investing in circular economy initiatives in the PV sector can reduce this dependency on the external market and diminish the vulnerability regarding the supply of those materials.

2.2 Perspectives on the circular economy in the PV sector

Many different definitions of circular economy can be found in academic and grey literature. However, it is possible to identify some common points between them. Kirchherr (2017) analysed 114 CE definitions, confirming this variety of existing concepts. Wautelet (2018) mentioned that the different types of definitions for CE aim to use resources more efficiently and reduce pollution. According to the Ellen MacArthur Foundation, the circular economy approach proposes that society rethinks how we design, make and consume things, consider the planetary boundaries, and focus on optimizing, restoring, and regenerating the materials. Therefore, based on the CE concept, the materials and products should be designed in a sustainable way, used for a more extended period to avoid or reduce waste disposal, preventing pollution and other impacts (Ellen MacArthur Foundation, n.d.). The European Commission proposes a very similar definition for the circular economy, pointing out that "the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized" (COM(2015) 614 final, 2015).

In the solar sector, the CE approach is many times associated with the need of ensuring that this type of renewable energy technology is, in fact, sustainable, minimizing environmental impacts. According to Salim et al. (2019), it is essential to consider circular economy strategies such as repairability, reusability and recyclability in the end-of-life (EoL) management of its components to consider PV technology genuinely renewable and sustainable.

There are many views regarding how a circular economy scenario for the photovoltaic sector should look like. The majority of them differ in nuances only and usually consider a life cycle approach, linking the PV panels value chain to strategies such as ecodesign, reusability, recyclability and refurbishment. For example, Strupeit and Bocken (2019) used the ReSOLVE framework, connecting their six circular economy actions (Regenerate, Share, Optimize, Loop, Virtualise and Exchange) plus one more (Facilitate) to the value chain stages of the PV sector. Similarly, Farrell et al. (2020) present a butterfly diagram that correlates the life-cycle of a c-Si PV module, from the raw material extraction to the end-of-life phase, to the circular economy strategies like recycling, remanufacture, reuse/distribution and repair/maintain.

The Fraunhofer Institute (ISE) mentioned the necessity of closing the loop in the manufacturing phase and the whole value chain (design, distribution, use and end-of-life stages), as well as the importance of raising sovereignty by local manufacturing (Webinar INES/CEA, 2021). The Deutsche Umwelthlife (2021) informs in its white paper that there are three goals for a circular economy in the solar sector: (i) prevention of waste, meaning ecodesign of PV panels, enhancing recycling and repairability, as well as reduce/eliminate the use of hazardous components (ii) preparation for reuse, meaning that the reused PV panels are checked and repaired for reuse, and (iii) recycling, meaning the recovery of valuable resources and removal of harmful substances. Salim et al. (2019) presented a scheme that describes both the critical issues of a linear PV supply chain and the opportunities of a circular PV supply chain.

There are several opportunities and advantages of moving from a linear economy to a circular one in the solar power sector. According to Salim et al. (2019), this transition would enable several advantages to all the stakeholders involved, including (i) society, that would benefit from job creation in recycling and refurbish sectors and also from reduced exposure to pollutants ; (ii) manufacturers that would reduce their dependency on raw materials and could reduce their production costs when reducing materials; (iii) distributors and installers, that would have a better image and trust with their clients; and (iv) governments that would benefit from the reduction of the demand for imported raw material. Farrell et al. (2020) state that recycling activities would help to increase space in landfills, reduce the risk of leakage of hazardous materials to the environment and reduce emissions.

Despite the advantages and opportunities mentioned above, according to Jensen et al. (2020), little evidence shows that the development and deployment of renewable energy equipment such as PV panels are being carried out on a big scale considering the circular economy approach. Strategies regarding recycling and resource recovery of these panels' components are not being seen as a priority by the companies because, for them, decommissioning of this equipment is currently not an issue (Jensen et al., 2020).

Section 2.3.1 shows the importance and main characteristics of the following circular economy strategies for PV waste management: ecodesign, reuse and recycling. The status, drivers and barriers of the three strategies are presented in sections 4 and 5.

2.2.1 Ecodesign of PV panels

Some authors highlight the definition and importance of ecodesign practices in the solar sector. Farrell et al. (2020) and the European Commission (COM(2020) 98 final, 2020) consider ecodesign or design for circularity as the practice of designing PV panels that are easy to disassemble, repair, recycle and refurbish. Salim et al. (2019) mentioned that the design for the environment could prevent the generation of hazardous waste. Chowdhury et al. (2020) point out that ecodesign can help decrease the environmental impact of solar products and contribute to the conservation of resources, especially when using recycled components in the manufacture of new PV panels. Another factor that contributes to the practice is related to the importance of reviewing the use and even the replacement of some valuable materials, such as silver, due to the growing demand for solar energy and the need to guarantee the supply of raw materials for the production of PV panels (PV Magazine, 2020).

However, due to the fact that the photovoltaic modules are planned to be resistant, lasting for many years, their layers are strongly connected, which makes it difficult to be recycled or refurbished (Farrell et al., 2020). Therefore, according to the European Commission (European Commission, 2020b), most PV panels available in the market nowadays are not designed to be circular, resulting in difficulty to reuse the PV panels and to recover its components.

2.2.2 Reuse of PV panels

When a PV panel is repaired and refurbished, its useful life is extended, making it possible to reuse it. These activities can prevent PV modules from prematurely entering the waste stream (PV Cycle & IMEC, 2021), reducing the amount of waste generated as well as the extraction of valuable raw materials and, consequently, lessening the environmental impact.

When a PV panel reaches its end-of-life after 25 to 30 years of use, it is estimated that it still possesses approximately 80% of its initial power generation capacity and, therefore, can be reused (Majewski, 2021). In addition, around 45% to 65% of the PV panels damaged during the production, transportation or during the first four years of function can be refurbished or repaired (Tsanakas et al., 2019). Presently, these sources of discarded panels represent up to 80% of the current PV panel's waste streams (Tsanakas et al., 2019). However, from 2030 on, when large amounts of PV panels are expected to reach their end of life, this proportion will probably change.

The type of failures and damages can determine if the PV panel will be repaired or not (Tsanakas et al., 2019). Usually, these failures are related to extreme weather events (that might increase due to climate change), transportation, quality of the product and lack of maintenance. Another aspect that can contribute to the generation of waste before the time expected is the financial incentive to replace old but still functioning modules with new and more efficient ones (Majewski, 2021).

2.2.3 Recycling of PV panels

The recycling of PV panels promotes the recovery of valuable materials and reduce the waste generated. This practice contributes to reducing hazardous materials sent to landfills and, consequently, less risk to the environment and human health (Salim et al., 2019). In addition, recovering materials, such as silicon, can benefit the whole PV value chain, reducing the dependence on external raw materials and minimizing the energy needed in the manufacturing process (Deng et al., 2020).

Recycling activities can be classified into two types: (i) bulk recycling, which is the one used to recover materials of high mass, such as glass and aluminium, and (ii) high-value recycling, which is the one used to recover bulk materials as well as valuable materials, such as metals and semiconductor (Wade et al., 2017). Furthermore, the three different technological processes to recycle PV panels are mechanical, thermal and chemical, and each of them can be used alone or in combination. The quality and value of materials recovered are affected by how and in what order these processes are used (Farrell et al., 2020).

The metals in PV modules, such as silver and copper, are difficult and expensive to recover, demanding higher energy, materials and labour, as well as generating waste. Despite corresponding to less than 1% of the total mass in PV panels, they can be a significant source of revenue (Heath et al., 2020).

2.3 Tools and frameworks to assess the circular economy

There is a clear need to assess and measure the state and progress of CE. According to the OECD (2020), there are four reasons to measure the status, impacts, and progress of a circular economy: increasing awareness, incentivising actions, measuring performance, and assessing results. The OECD also affirmed that what is not measured cannot be improved (OECD, 2020). At last, Saidani et al. (2019) point out the lack of targets, indicators and an evaluation framework as one reason why companies do not transition to CE solutions.

However, there are some obstacles to be faced with circular economy measurement. According to De Pascale et al. (2021), assessing circular economy implementation and progress is still challenging. Avdiushchenko and Zajac (2019) affirmed that although the circular economy concept has been implemented from micro to macro levels, the number of studies related to assessing circular economy for European regions, countries, business and processes is still limited. Smol et al. (2017) point out that there is no established framework for determining how well a product or organization transitions from a linear to a circular operation mode. According to Parchomenko et al. (2019), although there is a wide variety of measurement approaches that can evaluate the progress of the implementation of the circular economy, no monitoring framework that is generally accepted exists.

There are some tools to measure the circular economy, indicators being one of them. According to Saidani et al. (2019), indicators can help companies and policymakers to establish targets and monitor their progress. The same author has identified 55 sets of circular indicators created by consulting companies, researchers and governmental and non-governmental agencies, with different scopes, aims and utilization. De Pascale et al. (2021) identified 61 circular economy indicators, and The OECD Inventory of Circular Economy Indicators identified more than 400 indicators related to CE (OECD, 2020). Some examples of the circular economy indicators are the Circular Transition Indicators, from the World Business Council on Sustainable Development (WBCSD), the Circular Economy Monitoring Framework from the European Commission and the Material Circularity Indicator and the Circulytics, both from the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017).

Although the number of circular indicators has increased in recent years, there are some challenges to be addressed. Saidani et al. (2019) point out a need for further research into their classification, completeness and potential use from a business or political perspective. Some common challenges identified by the OECD (2020) for circular economy indicators are (i) non-existence of an agreed definition regarding the circular economy concept, resulting in the difficulty of creating an indicator since it is not clear what to measure (ii) lack of harmonized and consensual measurement framework and methodology for the circular economy. Furthermore, according to Parchomenko et al. (2019), many of the metrics focus on waste management, mainly resource and recycling efficiency and waste disposal. A few of them are linked to the maintenance of the value, one of the CE principles. Consequently, there is a fragmented and limited perspective due to the deficiency of indicators focusing on other themes, resulting in a lack of a system approach (OECD, 2020; Parchomenko et al., 2019).

A system-based approach is important because it enables the presentation of information from a broader perspective, concisely, taking into account multiple factors. It will help understand the context (laws, business activities, market, users, actors) and current linear trends in place, identifying priorities for the transition to a circular economy (Iacovidou et al., 2020). In that sense, an approach that considers the system dynamics and perspective and that consequently can be used to assess circular economy status is the Technological Innovation System (TIS) framework. The TIS is a well-known framework usually utilized to understand and analyse the transition to some technologies through the analysis of key factors and its drivers and barriers (Bergek et al., 2008). The following section will explain this framework in more detail.

2.3.1 The technological innovation system (TIS) framework

According to Hekkert and Negro (2009), the technological innovation system (TIS) was defined by Carlsson and Stanckiewicz, in 1991, as "a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology."

Bergek et al. (2008) created a framework based on this concept to "analyze a TIS, describing and assessing performance and identifying key policy issues". This framework maps (i) the structural features and dynamics of a TIS and (ii) the dynamics of several key factors (or functions) that impact the development, diffusion and utilization of the technology and, therefore, the performance of the innovation system. The framework is composed of three structural components, seven functions and six steps (Bergek et al., 2008), as described below:

- Three structural components: actors, networks and institutions. The idea is that the actors are linked through networks and generate products, knowledge and technologies based on an institutional structure (norms, rules, standards) (Markard et al., 2015).

- Seven functions: knowledge development (scientific, market, production and technological), resource mobilization (financial and human capital), market formation (the product users, the purchase process, demand profile, size, institutional stimuli and the role of standards), influence on the direction of search (factors that influence organizations to work with and become part of the TIS development), legitimization (comply with legislation and standards and needs to be socially accepted and desirable by actors), entrepreneurial experimentation (enables technological and innovation development), development of external economies (used to measure the positive dynamics of the other six functions). The seven functions are used to assess the performance and weakness of the system and suggest recommendations on how to overcome those weaknesses (Bergek et al., 2008; Markard et al., 2015).

- Six steps: 1) starting point: defining the TIS in focus; 2) structural components, 3) functions, 4) assessing functionality & setting process goals, 5) inducement & blocking mechanisms; and 6) key policy issues.

More information about each component and each factor is detailed in Chapter 4.

The TIS framework is multi-disciplinary (Markard et al., 2015) and can be used to evaluate emerging innovation systems. It also analyses the dynamics of each one of the seven functions mentioned above and the interaction between them. When there are positive interactions between the functions, it shows that the system is working well, resulting in the development, diffusion and use of the technology (Hekkert & Negro, 2009). Figure 2-2 illustrates the framework[1].

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[1] The step number 5 was slighlty changed from ”inducement &blocking mechanisms” to drivers and barriers.

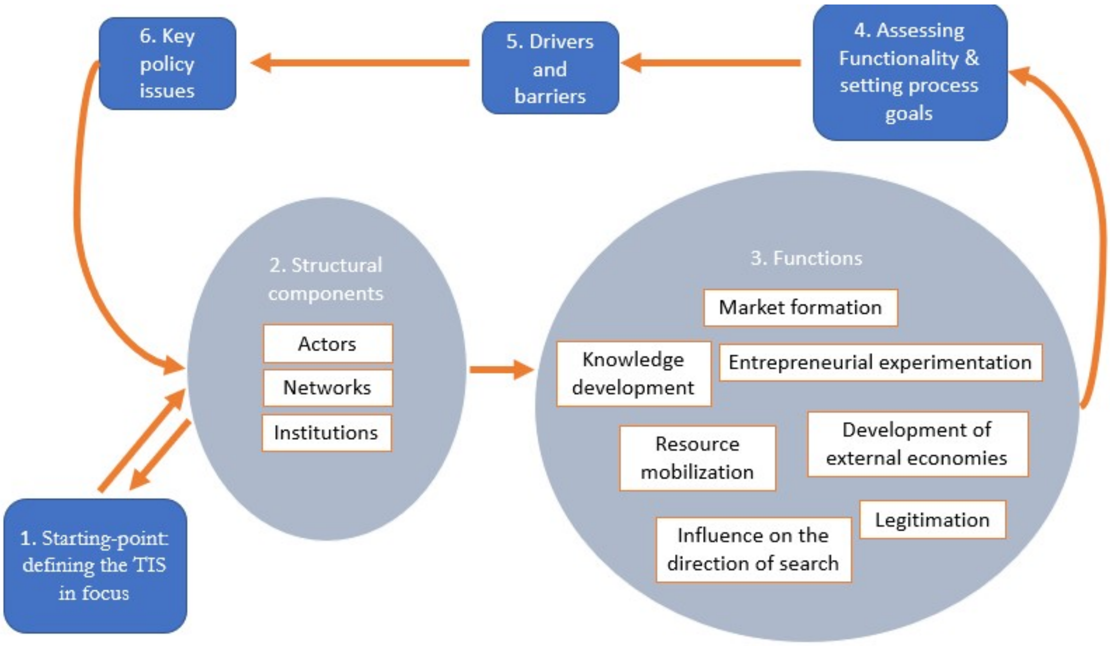


Figure 2-2 The analysis scheme of the TIS European Circular PV Innovation System.

Source: Adapted from Bergek et al. (2008)

Many scholars have applied the TIS approach to analyse renewable energy technologies, including solar systems (Hekkert & Negro, 2009). Guzzo et al. (2021) stated that TIS has also been adopted to evaluate sustainability transitions. According to him, sustainability transitions happen because of the development and dissemination of innovations that can generate a smaller environmental footprint compared to the technology in place (Guzzo et al., 2021). However, the TIS framework application to resource recovery systems, i.e., to circular economy analysis, still must be comprehended entirely (Iacovidou et al., 2020). So far, and according to the author's best knowledge, it seems that there was only one attempt to apply TIS to a circular economy context, that was a master thesis from Utrecht University (Leendertse, 2016).

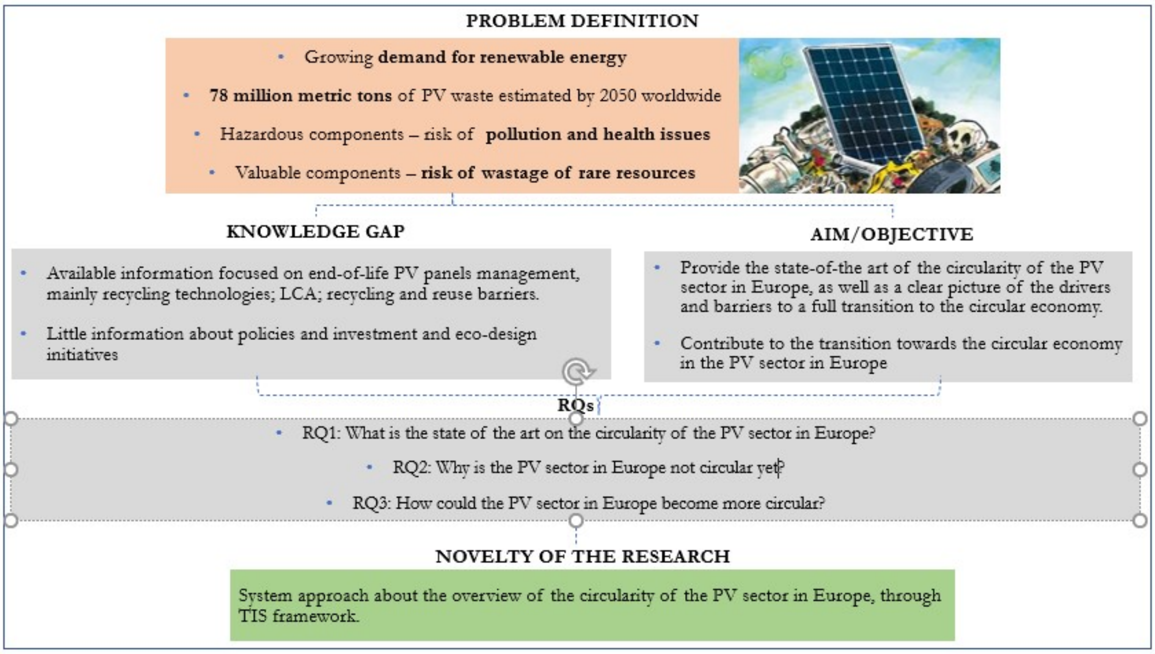
2.4 Conclusion of literature review

Based on the literature review presented in this Chapter, it is possible to realize that most of the research about circular economy in the PV sector focuses on recycling and on themes such as recycling technology, costs, and the waste issue. Furthermore, reuse is relatively less explored, and there is little information about ecodesign. At last, the data is fragmented, without a systematic approach to the status of the sector's circularity in Europe.

Moreover, the views about the circular economy in the PV sector presented by the scholars connect the strategies to the life cycle stages of the PV panel production. However, almost none mentions aspects such as investments, experiments, legitimation, market formation, actors and policies.

In addition, the academic and grey literature revealed that the existing circular economy indicators present some limitations, especially regarding the lack of systematic approach and the lack of assessment focused on a sector (only on companies and regions), Therefore, the TIS framework seems appropriate to assess the PV sector's circularity, answering the three research questions. This is because the framework enables a systemic view based on many different aspects not well explored before by the academic literature in a complete and concise way. Furthermore, it helps to identify the barriers and opportunities to the transition to a circular economy. The TIS approach to the circular economy of the PV sector is novel.

Figure 2-2 illustrates the summary of the main goal of this thesis, based on the problem definition and knowledge gap, as well as the research questions and novelty:



PROBLEM DEFINITION

- Growing **demand for renewable energy**
- **78 million metric tons** of PV waste estimated by 2050 worldwide
- Hazardous components – risk of **pollution and health issues**
- Valuable components – **risk of wastage of rare resources**

KNOWLEDGE GAP

- Available information focused on end-of-life PV panels management, mainly recycling technologies; LCA; recycling and reuse barriers.
- Little information about policies and investment and eco-design initiatives

AIM/OBJECTIVE

- Provide the state-of-the art of the circularity of the PV sector in Europe, as well as a clear picture of the drivers and barriers to a full transition to the circular economy.
- Contribute to the transition towards the circular economy in the PV sector in Europe

RQs

- RQ1: What is the state of the art on the circularity of the PV sector in Europe?
- RQ2: Why is the PV sector in Europe not circular yet?
- RQ3: How could the PV sector in Europe become more circular?

NOVELTY OF THE RESEARCH

System approach about the overview of the circularity of the PV sector in Europe, through TIS framework.

Figure 2-3 Representation of the problem definition, knowledge gap, aim, research questions and novelty of the research.

Source: Own elaboration

3 Research Design, Materials and Methods

This section of the thesis will present the research design, the methods applied to the research regarding collection and analysis of data, as well as the techniques used to ensure validity.

3.1 Research Design

In response to achieving the aim and answering the research questions of this thesis, it was decided to use a case study approach, which, according to Baxter and Jack (2015), "ensures that the issue is not explored through one lens, but rather a variety of lenses which allows for multiple facets of the phenomenon to be revealed and understood". Yin (2003) stated that the case study approach could be used to help to answer "why" and "how" questions and to understand contextual conditions that are important to assess the phenomenon under analysis. Therefore, the case study method seems appropriate to this research, which seeks to understand the current European context regarding the circularity of the photovoltaic sector through seven different lenses (functions) established by the TIS framework. Furthermore, the case study approach will also help to understand the why (RQ2) and how (RQ3) questions. The case study of this research is, more specifically, the circular PV innovation system in Europe.

The choice of the system approach, through the TIS framework, made sense to analyze what Europe (its actors, networks and institutions) is doing towards PV circularity, since a system is defined as "a group of components (devices, objects or agents) serving a common purpose, i.e., working towards a common objective or overall function" (Bergek et al., 2008).

Moreover, it was defined that (i) the system under study (TIS) is the European Circular PV Innovation System, and (ii) the focal object of investigation is a set of processes and technologies in relation to ecodesign, reuse and recycling of PV panels. Typically, the focal object of investigation in studies using the TIS framework is an innovative technological product. In this thesis, an adaptation to the framework was made to align with key features of a CE, including a redesign of products, processes and strategies along the entire value chain.. At last, the understanding of technological innovation as a process is also aligned with the definition of eco-innovation provided by Smol et al. (2017): *"the production, assimilation or exploitation of a product, <u>production process</u>, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts on resources used (including energy use) compared to the relevant alternatives"*.

Since the European Circular PV Innovation System is an emerging system, the TIS seems a suitable framework to assess this system's actual performance and demonstrate how developed and diffused the new technology (ecodesign, recycling and reuse of PV panels) is in Europe. Through the study of the actors, network, institutions, key functions current in place in Europe, the aim is to have an overview of the circularity of the PV panels in the region (RQ1), as well as the main barriers (RQ2), drivers, key policies, goals and opportunities (RQ3), answering the three research questions of this thesis, as illustrated by the Figure 3-1 below:

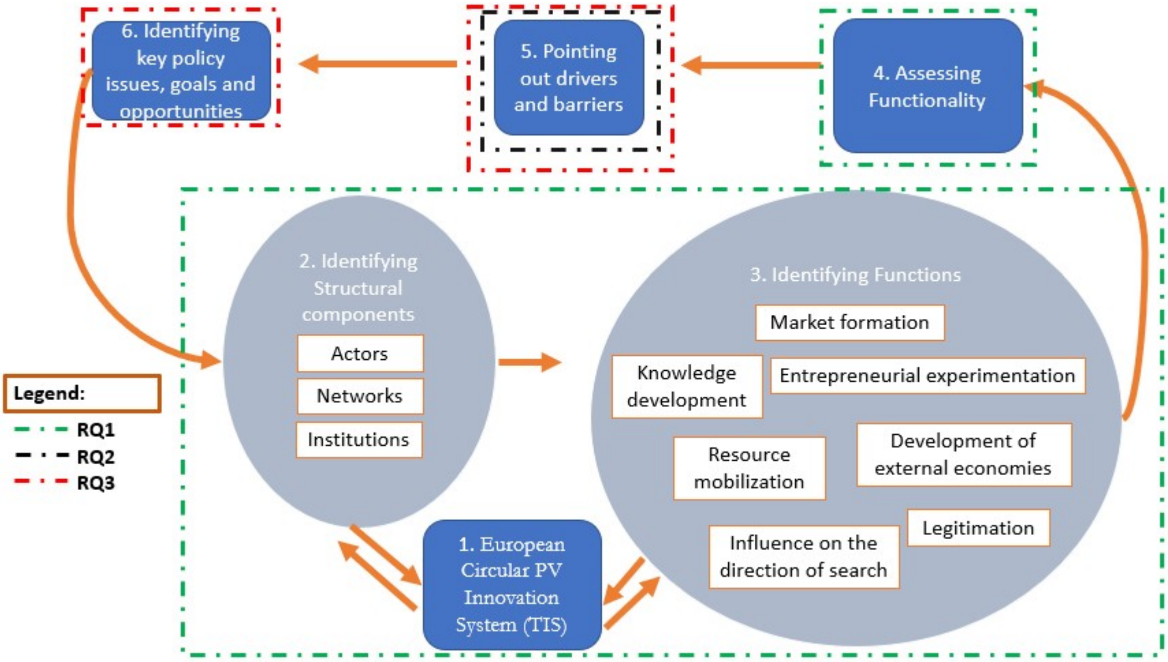


Figure 3-1 – The TIS Framework and the research questions

Source: Source: Own elaboration based on Bergek et al. (2008)

Some adaptations were made regarding the TIS framework suggested by Bergek et al. (2008), such as (i) the process goals originally included in step four were moved to step six; (ii) step six, which originally was referring only to the key policy issues, now also includes goals and opportunities. The author thought it would make more sense to set the goals after identifying the barriers and drivers and not before. In addition, identifying opportunities linked to goals and key policies can help to respond to RQ3.

In addition, a combination of deductive and inductive approach was used. Through the deductive method, the study was conducted based on established theories and concepts such as the circular economy and the TIS framework. In order to complement this approach, observations from the interviews and webinars were used in an inductive way to guide the research, also contributing to enlarge the applicability of the TIS framework to circular economy contexts.

3.2 Methods used to collect data and materials collected

The materials collected for this thesis were based on three different sources: literature review, webinars and interviews. The literature review focused on circular economy actions related to PV panel waste. To identify and select relevant data, some keywords were used to search materials, such as photovoltaic panels and waste, circular economy and PV, circular economy initiatives in the solar sector in Europe, circular economy policy in the PV sector, circular economy investments in the PV sector in Europe, etc. Furthermore, some techniques were used to identify relevant literature, such as snowballing and talking to experts in the field, mainly from companies and an academic research member of the CIRCUSOL project, explained in Chapter 4.

Regarding academic literature, the articles were searched in Google Scholar and accessed through Lund University and CEU library databases. Regarding grey literature, reports and press releases from key organizations dealing with photovoltaics, such as IRENA – International Renewable Energy Agency, IMEC - Interuniversity Microelectronics Centre, IEA – International Energy Agency, ISE – Fraunhofer Institute for Solar Energy Systems and SolarPower Europe were analyzed. In addition, articles from magazines such as PV Magazine and websites of European projects and companies involved with circular economy initiatives in the PV sector were also assessed. The grey literature played an essential role in this research, adding more recent and practical knowledge since the circular economy subject is relatively new in the solar sector. In total, around 45 articles and 15 reports were analyzed.

For the empirical study, webinars and interviews were used as primary sources of data. This choice was made after performing a gap analysis between the information collected from the literature review and the TIS framework. In order to collect the missing data, it was decided to attend webinars and interview actors that were involved directly with circular economy activities in the solar sector in Europe. About the webinars, the author attended three events, being one of them a three-day seminar in March 2021 that focused on circular and sustainable initiatives in the PV sector around the world. Some of the presenters were asked to be interviewed for this thesis. Besides, the author was invited and attended a stakeholder webinar organized by the European Commission regarding discussions about the future ecodesign and energy label legislation.

Regarding the interviews, 12 semi-structured interviews lasting approximately one hour were conducted via Zoom with people responsible for the sustainability area of research institutes, government (European Commission), industry associations, a Horizon 2020 project consortium and companies that work with recycling, reuse and ecodesign strategies in the solar power industry. The interviewees were selected based on their knowledge, expertise and circular initiatives to seek validation and get additional information from a practical perspective related to the main items identified in the literature review. The list of interviewees and webinars are described in Appendix 1. The main interview questionnaire used for the interviews, based on the TIS framework, is available in Appendix 2. Some adaptations were made for each interview.

3.3 Methods used to process information

The content analysis method was selected for data analysis, specifically, the directed content analysis approach, which usually uses a theory to guide the initial codes (Hsieh & Shannon, 2005). Therefore, at first, the elements of the TIS framework were used as codes to organize data, and additional codes were created to analyse the information. Then, information gathered from the interviews, literature review, and webinars were analyzed to identify statements and opinions related to each one of those codes. Finally, regarding the barriers and drivers, the most common codes were identified.

3.4 Ensuring validity

To guarantee the trustworthiness and validity of this research, well known and recognized research methods were used, such as case study and content analysis approach. The triangulation approach was also applied for this qualitative research to help to test the convergence and validity of the collected data from various sources (Carter et al., 2014). Snowballing technique (Atkinson & Flint, 2001) was also applied, helping to identify the further source of information, webinars and interviewees.

In addition, after conducting some interviews, it was possible to realize that the interviewees' explanations were converging to the same pattern of an answer, demonstrating and ensuring the validity of the techniques used. Furthermore, the broad and diverse range of interviewed actors enabled different views and perspectives about this research topic, contributing to its quality and validation.

Also, weekly meetings between the author and the thesis supervisor, as well as peer review sessions moderated by the IIIEE, helped to review the work and to make decisions about methodology, structure and approach.

4 Findings and results

This chapter presents the status of the TIS European Circular PV Innovation System, taking into account the TIS Framework developed by Bergek et al. (2008). The subsections are described below:

- Section 4.1: illustrates step 2 of the TIS framework, with the structural components of the TIS, meaning the actors, networks and institutions (policies and standards).

- Section 4.2: represents step 3 of the framework, with the seven functions of the TIS, which are market formation, knowledge development, entrepreneurial experimentation, resource mobilization, development of external economies, influence on the direction of search and legitimation.

The information presented, based on the literature review, webinars and interviews, provides answers to the RQ1 of this thesis, i.e., the state of the art of the circularity of the PV sector in Europe. The findings also answer the RQ2 (barriers to the full transition to the CE in the PV sector); however, they will be further discussed in the next Chapter. At last, the drivers, which are part of the RQ3, will also be presented in this Chapter. Still, the other components of this research question (goals, key policy, and opportunities) will be introduced and discussed in Chapter 5.

The quotes from the interviews included in this chapter are presented as codes (e.g., R1, R2…), according to the classification shown in Appendix 1.

4.1 The structural components of the TIS: actors, networks and institutions

The actor, networks and institutions contribute to the development, use and diffusion of new products and processes, i.e., to the TIS (Bergek et al., 2008).

4.1.1 Actors

According to Bergek et al. (2008), the actors of a TIS can include companies of the whole value chain, research institutes, universities, industry associations, government, standard organizations, etc.

Therefore, for the TIS in focus, some of the main actors that are involved with ecodesign, reuse and recycling activities were identified and are listed below[2]:

- Manufacturers, recyclers and repair companies: play an important role in the development of ecodesign, recycling and reuse initiatives. Some examples are presented in section 4.2.4.2.

- Installers/distributors: can contribute to significant amounts of PV waste, mainly during re-powering and repairing the existing PV panels. In Europe, there are several companies installing and distributing PV systems.

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[2] Raw material companies were not included in the analysis of the TIS of this thesis. The example of actors mentioned in this chapter comes from various sources, such as literature review and interviwes (snowballing technique).

- Research institutes: responsible for the development of research of studies, technologies, new applications, etc. Some examples are Fraunhofer Institute-ISE; European Technology and Innovation Platform (ETIP PV); Interuniversity Microelectronics Centre (Imec); Umweltinstitut GmbH (Bifa); Flemish Institute for Technological Research (Vito), and the French National Institute for Solar Energy (INES).

- Universities: Responsible for academic content and publications, contributing to the knowledge development regarding information about ecodesign, recycling and reuse strategies, technologies, studies, etc. Some examples are The International Institute for Industrial Environmental Economics (IIIEE, from Lund University); Bern University of Applied Sciences, School of Engineering (BUAS); Trinity College Dublin.

- Government: The European Commission (EC), through its group of scientists represented in the Joint Research Center (JRC), and the Directorate General Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), have task forces to discuss current and future laws and its requirements regarding PV waste, its treatment and ecodesign initiatives. More information available in sections 4.1.2 and 4.1.3.

- Associations: Represent groups of stakeholders, such as SolarPower Europe; European Solar Manufacturing Council; International Renewable Energy Agency (IRENA); International Energy Agency (IEA); International Association of Electronic Waste Producer Responsibility Organization (WEEE Forum). More information about SolarPower Europe and IEA are in the next section.

- Producer Responsibility Organization (PRO): Represent the producers (manufacturers, importers and distributors) of PV panels, responsible for collecting and treating the waste through fees paid by the producers. The PRO aims to help the producers to comply with the Extended Producer Responsibility (EPR) established by law in Europe. Some examples are the Italian Eco-PV and the Belgium PV Cycle (more information in section 4.1.2).

- Standards organization: Responsible for preparing non-mandatory standards that help the development of the market and compliance with legislation. Some examples are the European Committee for Electrotechnical Standardization (CENELEC) and the North American NFS International Standard and Cradle-to-Cradle Products Innovation Institute.

- Non-Governmental Organizations (NGOs): This can play an important role to make the population, policymakers and companies more aware of the importance of CE strategies for PV panels. An example is the German NGO Deutsche Umwelthilfe.

4.1.2 Networks

According to Bergek et al. (2008), a network can be formal or informal. Their focus can be on technological tasks, standard development, market formation or policy influence. Some examples of the network are associations, consortiums, standardization groups, technology platforms, public-private partnerships, and projects involving a university and business partnership.

Some examples of ongoing networks that are connected to the development of activities related to ecodesign, reuse and recycle of PV panels are listed below:

- **CIRCUSOL**: It is a Horizon 2020 project running from 2018 to 2022, funded by the European Commission, involving 15 members from eight European countries. The members are five research centres and universities, nine industrial players from the PV and battery value chains, and one consultancy firm. The project aims to develop and implement circular business models for the solar power industry, especially the product-service system (PSS). Through this business model, the solar power supplier offers the service of installation and maintenance of PV panels to the customer instead of the product, and when the product reaches the end of its life, the supplier can decide if the panel will be reused or sent to recycling. Therefore, the idea is that the amount of waste can be reduced by extending the product's life. Moreover, the other deliverables of CIRCUSOL include protocols of certification and labels for reused/second-life PV panels, as well as methodologies and tools for circular business models, policy recommendations and a platform/database with information about the production, installation and use of the PV panels. The goal of this project is to facilitate and formalize the activities of repair, reuse and recycling of solar modules (CIRCUSOL, n.d.).

- **Collective take-back scheme organized by PV Cycle:** A collective take-back scheme founded in 2007 and based in Brussels, focused on PV panels and other EEE. They represent the manufacturers, importers and rebranders of EEE products, taking care of the management of their WEEE through its national representations and partnerships around Europe (PV Cycle, n.d.).

- **Sustainability Task Force from SolarPower Europe**: It is an association representing organizations and other associations of the whole value chain of the solar power sector. Together they work to expand the market, identify and share practices and organize advocacy activities in Europe (SolarPower Europe, 2018). SolarPower Europe has a Sustainability Task Force with activities such as participation in discussions regarding new legislation created by the European Commission (Ecodesign study, for instance) and publication of factsheets related to environmental issues regarding solar power. The Task Force has around 40 members (SolarPower Europe, n.d.).

- **Task 12 from IEA-PVPS**: The Photovoltaic Power Systems Programme of the International Energy Agency (IEA) has several research tasks, one of them being the Task 12 – PV Sustainability Activities. This Task aims to accelerate and develop international knowledge and collaboration regarding sustainability issues in the PV sector. One of the objectives is to search for end-of-life options for PV panels by assessing circular economy strategies. Some of the European companies that participate in the group are PV Cycle, Vito and SolarPower Europe. Around 20 reports were produced, including the one in conjunction with IRENA, in 2016, called "End-of-Life management of Solar photovoltaic panels" (IEA-PVPS, n.d.).

- **Solar Photovoltaics project from EC:** This project was created in 2017 to develop a study regarding the feasibility of implementing four policies: Ecodesign legislation, Energy Label, Ecolabel and Green Public Procurement (GPP). In 2020, after the mentioned study, the group started to analyse the requirements for the Ecodesign and the Energy label, with the plan to end in 2022. Furthermore, this project is coordinated by DG GROW with the support of JRC and has continuous consultation with actors of the whole PV value chain (European Commission, n.d.a).

4.1.3 Institutions

The institutions are laws, standards, rules, as well as culture and routines (Bergek et al., 2008).

Policies:

The main legislation that introduces the importance of circular economy to the PV panels products is the Directive 2012/19/EU, also known as the WEEE Directive, which regulates waste management from electrical and electronic equipment, including the photovoltaic panels. According to the Directive, producers, importers, and distributors are responsible for the proper treatment of the PV panel's waste and should comply with specific targets for recovery and recycling. Therefore, for the different categories of the equipment, the Directive (Annex V) sets out specific recovery targets. For large PV panels (any external dimension more than 50 cm), 85 % of them shall be recovered, and 80% shall be prepared for reuse and recycling. For small PV panels (no external dimension more than 50 cm), 75 % of them shall be recovered, and 55 % shall be prepared for reuse and recycling (DIRECTIVE 2012/19/EU, 2012).

Article 7 of the WEEE Directive sets the collection target, which refers to all WEEE, i.e., no separate target for each category or any specific category. Therefore, the collection target for all types of equipment, including solar modules, is 85% since 2019. According to a report conducted by the European Commission (COM(2017) 171 final, 2017), it was concluded that it was not appropriate to set individual collection targets in the WEEE Directive at that stage.

In order to meet the targets and requirements of the Directive, the producers of PV panels must ensure a take-back scheme of the products by either implementing and operating their own scheme or joining a collective one. This means that those producers are also responsible for organizing the collection and treatment of their end-of-life PV panels without charging the panel owner. The revision process regarding the WEEE Directive is planned for 2023, and any proposal for its revision will follow in the years after that (European Commission, n.d.b).

Although the WEEE Directive encourages the ecodesign of EEE products, it does not establish specific requirements for it. These requirements are being discussed by the European Commission, which launched a report in 2020 with the assessment of the feasibility of implementing the four following policies: The Ecodesign legislation, the Energy Label, the Ecolabel and Green Public Procurement (GPP). The first two would be mandatory, and the last two would be voluntary. The report concludes that the ideal scenario would combine the Ecodesign legislation, the Energy label and the GPP (European Commission, 2020b).

The European Commission is currently discussing the potential regulatory measures of the Ecodesign legislation and Energy label. According to the "Second Stakeholder webinar on solar photovoltaic modules, inverters and systems" that took place in April 2021, the requirements that are being considered for the Ecodesign legislation are durability, repairability, recyclability, among others. The draft of the legal proposal is planned to be released in 2021 and the final document in 2022 (European Commission, 2021b).

Another relevant policy is the New Circular Economy Action Plan, launched in 2020. The Plan incentivizes and highlights the importance of having a new model for the European economy that opposes the linear economy model of make-take-dispose. It includes measures to empower consumers and public buyers, to guarantee less waste, to make sustainable products and services, focusing on some sectors such as electronics, batteries and food. In addition, the Plan includes actions to make sustainable products and services along its entire life cycle, incentivizing companies to have circular business models in order to increase their profitability and protecting them from resource price fluctuations (COM(2020) 98 final, 2020).

Standards and ecolabel:

There are three non-mandatory standards related to the circular economy in the PV sector. Two of them are European, created according to Article 8 of the WEEE Directive, with the aim of guiding operators involved in the treatment of PV panels on how to perform collection and treatment activities. The third one is North American, establishing sustainability performance criteria for PV panels. Based on this American standard, the EPEAT ecolabel was created by the U.S.-based Global Electronics Council, helping purchasers to identify sustainable PV products. The NFS standard and the EPEAT ecolabel were considered in this research because of the potential influence on other countries, including European ones. The details of each one of the standards are described in Table 4-1.

Table 4-1 Standards regarding circular economy initiatives for photovoltaic panels.

Standard/Ecolabel	**Title**	**Mandatory?**	**Created by**	**Description**	**Year**
EN 50625-2-4:2017	Collection, logistics & treatment requirements for WEEE - Part 2-4: Treatment requirements for photovoltaic panels	No	CENELEC-European Committee for Electrotechnical Standardization	European Standard (EN) with instructions to help operators in meeting the requirements for collecting and treating PV panels, in accordance with the WEEE Directive, Article 8. It includes steps regarding the separation of PV modules by type and materials fractions.	17/11/17
TS 50625-3-5:2017	Collection, logistics & Treatment requirements for WEEE - Part 3-5: Technical specification for de-pollution - Photovoltaic panels	No	CENELEC - European Committee for Electrotechnical Standardization	European Technical Specification (TS) should be used in conjunction with the EN 50625-2-4.	17/11/17

NSF 457 – 2019	Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters	No	NSF International Standard / American National Standard	Standard that establishes lifecycle-based sustainability performance criteria for PV modules and inverters. The seven criteria performance categories are management of substances, preferable materials use, life cycle assessment, energy efficiency & water use, end-of-life management & design for recycling, product packaging, and corporate responsibility.	22/07/19
EPEAT ecolabel	EPEAT Photovoltaic Modules and Inverters Category criteria [based on NSF/ANSI 457 – 2019 Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters	No	The Global Electronics Council - The USA	Ecolabel that establishes lifecycle-based sustainability performance criteria for PV modules and inverters. Help purchasers to identify sustainable PV products. Include criteria such as the sourcing of materials and end-of-life recycling. There are three categories of performance (gold, silver and bronze).	October 2020

Source: Based on Lorenzen and Scher (n.d.); NSF International Standard American National Standard (2019); European Commission (2021a); CENELEC (2017); *Franz and Piringer (2020).*

In February 2021, the Commission published a study on quality standards for the WEEE treatment. The study proposes additional requirements for WEEE treatment, including the treatment of photovoltaic panels (European Commission, 2021a).

Culture/routines:

Considering that culture and routines are related to awareness, the interviewees were asked about the current level of awareness of the public, policymakers and companies about the importance of CE strategies in the PV sector and the waste problem. Many interviewees said that it is an emerging and increasing awareness in general, but it is still low, especially when it comes to the general public (R1, R3, R6, R9, R12). According to some of the interviewees, PV panels are generally considered a sustainable technology. Therefore, many people are usually unaware of its composition and the waste issue (R5, R6). Regarding the companies, a few of them said that the industry has a clear understanding of the problem (R3, F9). About the policymakers, some of the interviewees said it is possible to see that the awareness is increasing (R1, R6), especially due to the WEEE Directive, the New Circular Economy Action Plan, the funding assigned to circular economy research projects in the Horizon 2020 program, the ecodesign study and the discussions about the new regulations conducted by the European Commission.

According to Salim et al. (2019), there are two critical challenges related to people's awareness in general. These are (i) consumer perception about the reduced efficiency of recycled materials and reused panels, and (ii) the low effectiveness of the policies in place to raise people's awareness regarding the importance of returning PV panels to a collection point at its end of life.

4.2 The seven functions of the Technological Innovation System

In this section, the seven functions of the TIS framework are analysed to see the status of the European Circular PV Innovation System in terms of these key processes.

4.2.1 Influence on the direction of search

This function characterizes the factors that influences organizations to work with and become part of the TIS in development. These factors are incentives, pressure, visions, beliefs, expectations, policies, customer demand, technical issues and crisis regarding the current business (Bergek et al., 2008).

Regarding the TIS of this research, i.e., the European Circular PV Innovation System, some factors have influenced organizations to work with initiatives related to ecodesign, recycling, and reuse of PV panels. Based on the interviews, the main factors and drivers are:

a) The growing demand for solar energy technology resulting from agreements and requirements to mitigate climate change (R1, R6).

b) The growing generation of PV waste (R1, R6, R7, R9, R13).

c) Pressure from a political and community side (WEEE legislation, ecodesign study, IRENA study) (R3, R6, R9).

d) The willingness to be less dependent on importing raw materials and PV modules (R4, R6, R8, R10, R11).

e) Potential for recovery of raw materials and the consequent economic and environmental benefits (R1, R3, R5, R7, R9, R10, R11, R13).

f) European funding projects such as Horizon 2020 (R6, R8).

g) Product differentiation strategies among solar firms (R7, R8, R11).

h) Cost reduction in the manufacturing process due to eliminating costs linked to logistics and raw materials importation (R11).

i) Positive environmental footprint and truly sustainable energy technology (R1, R6, R9).

j) Strong demand for outdated modules to keep existing installations running and to repair them punctually (R12).

Item e), that is, the recovery of raw materials, was the most mentioned factor by the interviewees, followed by items b) the growing generation of PV waste, and d) the external dependency on raw materials and PV modules. Many scholars and institutes also mention the same three aspects (European Commission, 2020a; IRENA, 2016; ISE Fraunhofer, 2020a; Rabe et al., 2017), and they are also aligned with the New Circular Economy Action Plan.

According to some interviewees, the possibility of recovering materials from the PV panels, especially the valuable ones, presents an opportunity and advantage for the European economy since costs with the transportation of those materials and production of the PV panels would reduce. There is an opportunity to create a local market for recovered raw materials, creating jobs and reducing the dependency on the external supply chain. This dependency became more evident during the COVID-19 pandemic (R7 and R10), where people realized that supply chains are unstable. Furthermore, these advantages and opportunities are even more important for a continent that is resuming the discussion of producing PV panels more intensely (European Commission, 2020c) due to the ambition to install 35GW in the following years (SolarPower Europe, 2020).

4.2.2 Entrepreneurial experimentation

Entrepreneurial experimentation enables technological and innovation development, contributing to reducing uncertainty, the unfolding of the social learning process, and the evolution of a TIS, regardless of its phase (Bergek et al., 2008).

In the European Circular PV Innovation System, three types of entrepreneurial experimentation can be considered: funding, new entrants and new technologies. About the funding sources, the Horizon 2020 program is the biggest one in Europe related to research and innovation, with around eighty billion euro of budget available for seven years (European Commission, 2013). Some ongoing projects related to the circular economy in the solar sector received funding from the Horizon 2020 program. The projects are mainly related to circular business model development, recycling and raw material recovery, as detailed in Table 4-2.

Table 4-2 Current Horizon 2020 projects related to the circular economy in the PV sector.

Name of the H2020 project	**Description**	**Period**	**Members**
CIRCUSOL	"Circular Business Models development and demonstration for the solar power industry", with a focus on service-based ones (Product-Service System - PSS).	1 June 2018 to 31 May 2022	15 partners from 8 countries: Coordinated by VITO (Flemish Institute for Technological Research).

PVadapt	“Prefabrication, Recyclability and Modularity for cost reductions in Smart BIPV systems.” (design for recyclability)	1 October 2018 to 31 March 2022	18 partners Coordinated by Merit Consulting House sprl.
HighLite	“High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry.” (ecodesign)	1 October 2019 to 30 September 2022	18 partners Coordinated by Interuniversitair Micro-Electronica Centrum.
Trust-PV	“Increase Friendly Integration of Reliable PV plants considering different market segments” (reduction of failures, increase recyclability).	1 September 2020 to 31 August 2024	20 partners Coordinated by Accademia Europea di Bolzano.
BOOSTER	“Organic photovoltaics for eco-friendly buildings (non-toxic resources-ecodesign)”.	1 September 2020 to 31 August 2024	Coordinated by Armor AS.
Ramp-PV	“Raw material up-cycling for circular PV.” (recycling)	1 November 2020 to 31 October 2022	Coordinated by the French company Rosi.

Source: Own elaboration, based on research from the Community Research and Development Information Service - CORDIS website (European Commission, n.d.-c)*, using keywords such as “circular PV”, “recycling photovoltaic”, “reuse photovoltaic”.*

Regarding new technologies, the NICE is an example of a PV panel designed for circularity, developed by the French company Appolon Solar. The panel is encapsulant-free, which facilitates its recycling and reuse and reduces the amount of material used, saving costs of production (Tsanakas et al., 2019). The company participated in three different Horizon 2020 projects (Eco-Solar, Super-PV and PV-Adapt), contributing with knowledge through this technology (Appolon Solar, n.d.).

The Frelp by Sun and the ELSi recycling facilities are examples of new entrants. Frelp by Sun is located in Italy, owned by the Italian company TIALPI, and it received financial support from LIFE, another European funding program. According to TIALPI’s plan, the facility will start operating in September 2021. The technology used can recover 81% of the materials of the silicon-based PV panels, meaning the glass and aluminium parts (R13). The ELSi plant is in Germany, operated by the Geltz company, and was funded by Horizon 2020 from 2016 to 2018 (more details in section 4.2.3). The plant combines mechanical and chemical technologies to enable the recovery of silicon, aluminium, copper, silver, glass, lead, and tin from silicon-based PV panels (Geltz, n.d.).

4.2.3 Resource Mobilization

In order to evolve, the TIS needs resources, including financial and human capital (Bergek et al., 2008).

About the financial capital, from June 2015 to August 2024[3], at least ten projects related to recycling, reuse and ecodesign technologies, business models and strategies were funded by Horizon 2020, representing more than 74 million euro. The projects are shown in Table 4-3 below.

Table 4-3 Horizon 2020 projects related to the circular economy in the PV sector since 2016.

Name of the H2020 project	**Description**	**Period**	**Overall budget**	**Members**
CABRISS	“Implementation of a circular economy based on recycled, reused and recovered indium, silicon and silver materials for photovoltaic and other applications.”	1 June 2015 to 31 May 2018	9.266.682,65 €	16 partners from 8 countries: Six small and medium-sized enterprises (SMEs) 5 Industries 5 Research and Technology Organizations (RTO) Coordinated by CEA (French Alternative Energies and Atomic Energy Commission)
Eco-Solar	“40% eco-efficiency gains in the photovoltaic value chain with reduced resource and energy consumption by closed-loop systems” (reuse, recovery).	1 October 2015 to 30 September 2018	5.642.707,75 €	11 partners Coordinated by Syntef AS
ELSi	“Industrial-scale recovery and reuse of all materials from end-of-life silicon-based. photovoltaic modules.”	1 May 2016 to 30 April 2018	3.248.338,75 €	Coordinated by Geltz Umwelttechnologie Gmbh
CIRCUSOL	“Circular Business Models development and demonstration for the solar power industry”, with a focus on service-based ones (Product-Service System - PSS).	1 June 2018 to 31 May 2022	8.253.715,00 €	15 partners from 8 countries: Five research centres and universities, Nine industrial players from the PV and battery value chains, one consultancy firm. Coordinated by VITO (Flemish Institute for Technological Research).

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[3] The start year for the search of the projects (around 2016) was defined considering the IRENA study released at that time, because from that moment the problem of PV waste started to gain greater relevance amongst the actors.

PVadapt	"Prefabrication, Recyclability and Modularity for cost reductions in Smart BIPV systems." (design for recyclability)	1 October 2018 to 31 March 2022	11.067.125,00 €	18 partners Coordinated by Merit Consulting House sprl
HighLite	"High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry." (ecodesign)	1 October 2019 to 30 September 2022	15.087.603,61 €	18 partners Coordinated by Interuniversitair Micro-Electronica Centrum
PRO-S	"The first highly energy-efficient and eco-friendly bio based-photovoltaic module that works without sunlight or battery consumption for Smart buildings" (toxic-free and recyclable – ecodesign).	1 December 2019 to 30 April 2020	71.429,00 €	Coordinated by Proton New Energy Future Sl
Trust-PV	"Increase Friendly Integration of Reliable PV plants considering different market segments" (reduction of failures, increase recyclability)	1 September 2020 to 31 August 2024	12.984.222,50 €	20 partners Coordinated by Accademia Europea di Bolzano
BOOSTER	"Organic photovoltaics for eco-friendly buildings" (non-toxic resources – ecodesign)	1 September 2020 to 31 August 2024	8.196.473,75 €	Coordinated by Armor AS
Ramp-PV	"Raw material up-cycling for circular PV" (recycling)	1 November 2020 to 31 October 2022	1.003.500,00 €	Coordinated by the French company Rosi Solar.
TOTAL			**74.821.798,01 €**	

Source: Own elaboration, based on research from the Community Research and Development Information Service - CORDIS website (European Commission, n.d.-c) using keywords such as "circular PV", "recycling photovoltaic", "reuse photovoltaic".

Regarding human resources, six out of twelve interviewees said that their organizations have between 3 and 12 people working with CE (R1, R3, R5, R7, R8, R13). The other three reported that there are from 35 to 160 people working with this subject (R6, R9, R11). Three of them did not answer.

When the interviewees were asked about the skills that are missing on people working with CE strategies, the answers were:

i. Collaboration and information sharing throughout the supply chain.

ii. Education/lobbying/communication about CE strategies benefits and waste as a resource.

iii. Circular thinking/mindset.

iv. Long term strategic thinking.

v. The ambition of the industry to get circular.

Items (ii) is the most mentioned by the interviewees (R1, R7, R9, R10), followed by item (i) (R5, R8, R11). The lack of information sharing, transparency and collaboration was also mentioned by some scholars (Saidani et al., 2019; Salim et al., 2019; Sica et al., 2018). The technical skill was mentioned by many of them as one that is not missing (R7, R9, R10 and R11).

4.2.4 Knowledge development

This function measures the level of knowledge related to the TIS. The types of knowledge can be many, such as scientific, market, production and technological. The source of knowledge can also vary from research and development, imitation, production to learning from experiments and new applications. Some indicators can be used to assess the level of knowledge of a TIS, such as the number of publications, R&D projects, learning curves, patents, evaluation by managers and others (Bergek et al., 2008). Regarding the TIS of this research, some of those indicators are described in the following subsections.

Number of publications and magazines

The number of publications regarding circular economy strategies in the solar sector from 2005 to 2020 is presented in Figure 4-1, ranging from 14 to 154:

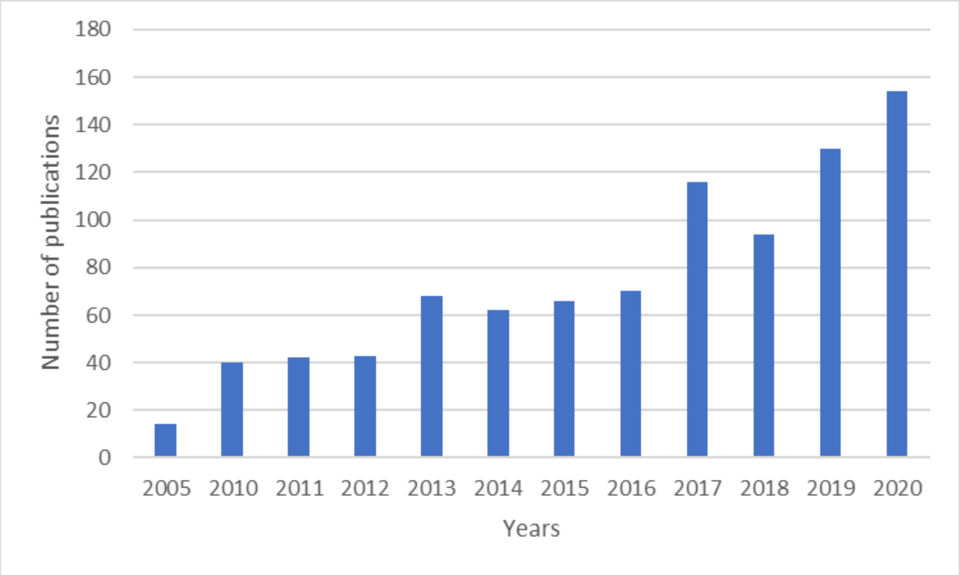

Figure 4-1 Number of publications related to CE in the PV sector between 2005 and 2020.

Source: Own elaboration based on Scopus website (Scopus, n.d.), using the keywords "photovoltaic circular economy", "photovoltaic AND reuse", and "photovoltaic AND recycling."

The PV Magazine launched in 2019, through the UP Initiative, a series of articles, webinars and roundtables to explore topics such as ecodesign, reuse and recycling of PV panels. The aim is to enable discussion and provide knowledge about a truly sustainable solar sector, identifying ongoing initiatives and areas of improvement. The themes discussed change every quarter of the year (PV Magazine, n.d.).

Horizon 2020 projects and task forces

Knowledge is also being generated regarding the circular economy by the Horizon 2020 projects mentioned in section 4.2.2, which are related to technological and business model creation. In addition, the technical/discussion groups discussed in section 4.1.2, such as the ones conducted by the International Energy Agency (Task Force 12 – PV Sustainability Activities), the Joint Research Center of European Commission (ecodesign study) and SolarPower Europe (Sustainability Task Force) also contribute to the knowledge development in the area.

Companies' initiatives

Some European companies are working with ecodesign, recycling and reuse initiatives in the solar sector. The learning processes resulting from those initiatives are important for the company itself, using the hits and misses to improve its actions. Moreover, other companies in the sector can benefit from this knowledge once they can rely on these initiatives to implement activities in their own companies. Some examples are listed in the following paragraphs.

Ecodesign:

The reduction of materials has been the most used practice in the design of PV panels in recent years. An example is silver, whose utilization decreased by 70% since 2010 (Heath et al., 2020). This material reduction practice is generally driven by factors such as efficiency, reliability and cost of photovoltaic panels, and not by environmental aspects (Tao et al., 2020).

Regarding the design for recyclability and reusability, there are some initiatives carried out by European companies. Solitek, a company located in Lithuania that is responsible for research, development, manufacture, sell and installation of PV panels in Europe (Solitek, n.d.), is currently investigating alternative materials for PV panels components intending to reduce toxic materials and enable the panel for recycling (Circusol, 2020). This test is being carried out with the support of the European Commission through the Circusol project. In addition, in 2020, the company´s PV panel was the first one in Europe to receive the Cradle-to-Cradle Silver Certificate, issued by the Cradle-to-Cradle Products Innovation Institute, which assesses quality categories such as material health and material reuse (Solitek, 2020)

DSM is a science-based global organization with the Advanced Solar business located in The Netherlands, which created the Endurance backsheet. This product is fluorine-free and recyclable through the process of re-melting and shaping (DSM, n.d.). Another example is the NICE technology from Appolon Solar, already mentioned in section 4.2.2.

Reuse:

Currently, the companies that are working with the activities of repair, refurbishment and/or reuse are not linked to the manufacturers or supported by them, being conducted in an independent way (Tsanakas et al., 2019). In Europe, there are some companies that are working or connected with this purpose:

- SunCrafter Gmbh, in Germany, which has high expertise in solar equipment maintenance and is responsible for transforming decommissioned photovoltaic panels into solar generators of a powerful low-voltage plug, upcycling them to be used in festivals, events, in communities that have no access to energy and in energy hubs for electric scooters (Suncrafter, n.d.).

- SecondSol, pvXchange and Solar-pur are German suppliers of solar energy equipment, selling refurbished second-life PV modules primarily to business-to-business companies (B2B). Installation, quality control and maintenance services are often offered by some of these firms, which are normally performed by PV installs or insurance companies with strong experience (Tsanakas et al., 2019).

- Rinovasol: German company that provide services of restoration, refurbishment and recycling of PV panels since 2014 (Rinovasol, n.d.).

Recycling:

Recycling PV panels in Europe began around 2012, after this type of EEE was included in the WEEE Directive in the same year. The majority of the companies that work with recycling PV panels do not have dedicated facilities for this type of waste, utilizing or changing existing EEE or glass treatment plants (Heath et al., 2020; Tao et al., 2020). Furthermore, only the bulky materials in silicon-based panels, such as aluminium, glass and copper, are typically recovered (Tao et al., 2020).

The largest facility that recycles only c-Si PV panels is located in France, belonging to the Veolia group, and received funding from the European Union (IEA-PVPS, 2019). The plant, founded in 2018, has a contract with the French unit of PV Cycle and plan to recycle up to four thousand ton of PV panels by 2022 (Veolia, 2018). Furthermore, it has a 95% recovery ratio regarding aluminium, polymeric materials, silicon cells, cables, connectors, and glass (Tsanakas et al., 2019). LuxChemtech, located in Germany and established in 2019, is another company focused on recovering materials such as glass, silver, indium, silicon, tellurium, etc. (LuxChemtech, n.d.).

Some companies work with the recycling of CdTe thin-film PV modules and operate in Europe for years (Heath et al., 2020). One example is First Solar, a North American company that, besides working with design, manufacture and selling of thin-film PV panels, also has recycling facilities, including one in Germany (First Solar, 2020). The achieved recycling rate of the PV modules is 90%, corresponding mainly to glass and frames and semiconductor materials. The glass industry usually uses the recovered glass, and the semiconductor is reused to produce First PV panels (First Solar, 2020). ANTEC Solar, a German company, is another example of a company working with the recycling of CdTe thin-film panels (Tsanakas et al., 2019).

4.2.5 Market formation

The market development is connected to the growth phase of the TIS. Therefore, for an emerging TIS, markets either do not exist or are not yet well developed. Furthermore, there are three phases of market formation: nursing, bridging and mature. In order to analyse the current TIS market phase and development, some aspects must be identified: the product users, the purchase process, demand profile, size, institutional stimuli and the role of standards (Bergek et al., 2008).

The market formation of the TIS European Circular PV Innovation System is described based on the aspects mentioned above. It is presented by circular product type, i.e., ecodesigned PV panels, recycled materials and reused PV panels.

4.2.5.1 The institutional stimuli

The institutional stimuli include legislation, policies and standards, as well as culture and routines that help create the market for circular economy strategies.

Culture stimuli – all circular products

As already mentioned before, the level of awareness about the importance of CE strategies in the solar sector is increasing. However, it is still low, which can be a barrier to market development. Furthermore, the interviewees indicated that, across all CE strategies, a key barrier to stimulate the market of ecodesign and reused PV panels and recycled materials is the long lifetime of PV panels and the consequent non-willingness to invest in CE initiatives. According to some of them, it is easy to bring CE innovations to a mobile phone because its average lifetime is around two years, but for PV panels, it is necessary to wait for around 25 years to find out if a technical innovation in the module works or if it causes problems.

Legislation, policies and standards stimuli

Ecodesigned PV panels

Legislation that stimulates the ecodesign of PV panels is currently under development, as can be seen from the discussions that are taking place about the requirements of the potential Ecodesign and Energy Label legislation (see section 4.1.3). These laws and ecolabels were the aspects most commented on by the interviewees to enable the formation of a market for ecodesigned PV panels (R3, R5, R8, R9, R11). The fact that most PV modules are currently manufactured in China should not prevent the solar industry from making investments in CE because it is envisioned that producers and importers will need to comply with the same rules of the future Ecodesign Directive (R2).

Regarding ecolabels, the only one available for PV panels is the North-American EPEAT Ecolabel, see section 4.1.3. Despite the importance attributed to this tool, none of the interviewed PV manufacturer companies has this certification. One of them reported that there is still not any customer demand for it (R11).

The lack of financial incentives was pointed out by some interviewees (R7, R9, R11) and by Salim (2019) as one of the main barriers to promote the design that facilitates PV refurbishment and recyclability.

Reused PV panels

Although the WEEE Directive has specific targets for recovery and preparation for reuse of PV panels, the market for reuse is mostly informal so far. The main barriers for the market development of used PV panels indicated by authors (European Commission, 2020b; Salim et al., 2019; Tsanakas et al., 2019) and interviewees (R1, R2, R6, R9, R10) are the lack of guarantee of performance, functionality, safety and quality of those reused PV panels, as well as the lack of rules and standards on labelling and testing to provide this warranty.

Other barriers pointed out by the interviewees are related to the low price of new PV panels compared to reused PV panels and the importance of creating financial incentives for the development of reused PV panels (R6, R10). The costs of second-hand products affect the willingness to pay for them. For such PV panels to be attractive and profitable, their price should be competitive, and it might not be so easy to do so considering repair and transportation costs. Furthermore, new panels are considered more efficient, resulting in more energy production (Smeets, 2020).

Recycled components

The WEEE Directive incentivizes the recovery, reuse and recycling activities for PV panels waste by establishing specific recovery targets and a general collection target, as mentioned in section 4.1.3. According to PV Cycle, from 2010 to November 2020, around 43.000 tons of PV panels were collected in Europe[4] (R2). The average recycling rate of PV panels across Europe and all photovoltaic technologies is 72%, and the average rate for other material recovery is 28% (R2).

As pointed out by the literature (Deutsche Umwelthilfe, 2021; Tsanakas et al., 2019) and by some interviewees (R9, R11), there is no specific recovery target for high-value materials in the WEEE Directive, which incentivizes only the bulk recovery (glass, aluminium and copper). Consequently, this lack of target in the legislation is considered a barrier to developing technologies that recover high-value materials and the development of the recycling market itself (R9, R11). The recovery of pure silicon is, for example, a big challenge due to technological and economic aspects (Franz & Piringer, 2020). Another complex factor related to the extraction of the PV panels components is the diversity of technologies and materials (Salim et al., 2019; Tao et al., 2020).

Other institutional stimuli for the market development of recycling initiatives are the European non-mandatory standards EN 50625-2-4 and TS 50625-3-5, and the EPEAT ecolabel, which considers end-of-life management as one of the criteria. All of them are voluntary tools, as mentioned in section 4.1.3.

Similar to the development of a market for ecodesigned PV, some of the interviewees said that the institutional changes that need to happen in order to incentivize the recycling market are related to the creation of ecolabels. Furthermore, some interviewees identified barriers specifically related to policies and legislation: the lack of economic incentives and the difficulty (time-consuming, costly) to move the recovered materials transboundary because they are seen as waste and not as a product (R9).

4.2.5.2 Users, purchase process and demand profile

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[4] Only business-to-business (B2B) direct activities

> *"You can achieve that everything is super circular, but what will the cost be? (…) it will pay back itself one point in time. But the question is, is the market ready for this now?" (R2)*

Ecodesigned PV panels

According to some interviewees, there is a lack of market demand for ecodesigned PV panels (R2, R8, R9). Therefore, the users and demand profile are not well established. For example, the Endurance backsheet of DSM, whose clients are mainly from China (75%), the lower price (compared to the traditional backsheets) and durability are the current drivers for customers (R11). Appolon Solar, on the other hand, has a more expensive technology than the traditional ones, and according to a company representative, it already has some possible European buyers, such as local government, companies, private people and house owners (R7).

Reused PV panels

Presently, the market for reused PV panels, which usually have lower lifetime expectations and performance, is focused on low-income countries and regions, such as Afghanistan, Pakistan and Africa, as stated by the literature (European Commission, 2020b; PV Cycle & IMEC, 2021) and one of the interviewees (R2). The lack of testing and absence of a warranty regarding the functionality of reused PV panels before it is exported to those regions is seen as one of the barriers for the development of the market for reused PV. According to one of the interviewees, it can result in a risk of exporting products that are not working anymore, i.e., products that are already waste (R9). It is also seen as a barrier to the development of a recycling market in Europe: *"80 per cent of the material which we would expect to be there for recycling is not there. And that's because it gets exported" (R9).* Therefore, this risk could be avoided by the creation of standards and rules (R10), as mentioned in subsection 4.2.5.1.

In Europe, a market for reused PV panels exists. However, it is small and usually concentrated in Western Europe, where used modules serve as a spare part in existing installations when damaged modules need to be replaced by very similar ones (PV Cycle & IMEC, 2021) (R12). For those cases, companies mentioned in section 4.2.4.2 provide repair and re-powering services and usually offer a warranty of two years (European Commission, 2020b). Another barrier pointed out by the interviewees is the lack of a market for reused PV in high-income countries due to reasons related to government incentives to deploy PV panels as well as high labour costs to perform activities such as testing and transporting of the reused PV panels (PV Cycle & IMEC, 2021) (R6).

Nowadays, the volume of PV waste is still low, being one of the barriers indicated by the interviewees (R1, R2, R6). Repair activities are usually only viable when the quantity is higher due to the costs related to transport and refurbishment (Tsanakas et al., 2019). However, as soon as the volume of waste starts to increase, the challenge will be to find a significant and sustained market for them (Tao et al., 2020).

Recycled PV panels

Currently, there is market demand for recycled glass of PV panels. This glass is used by industries other than the solar power industry because the quality of the recovered glass is not considered adequate enough for the manufacturing of new PV panels (R9). In general, however, some of the interviewees mentioned that there is little or no demand for recycled components of PV panels (R2, R8, R9) and that ecolabels could help to enable this market (R3, R6, R9).

Furthermore, according to the literature review and the interviewees, there are many barriers related to the recycling of PV systems, including but not limited to:

- environmental issues associated with the recycling process, such as the use of chemicals during the process, which can cause pollution and high energy use (Salim et al., 2019).
- not economically viable to recycle due to (i) small amount of waste (Deutsche Umwelthilfe, 2021; Salim et al., 2019) (R1, R2, R6), (ii) high cost of recycling (Deng et al., 2020), (iii) high transportation costs from long-distances (Salim et al., 2019), (iv) and lack of profitability (Salim et al., 2019; Tao et al., 2020).
- lack of economic incentives for recycling, such as subsidies, tax relief and increasing of raw material´s price (Salim et al., 2019).
- policies in place not effective in raising awareness and attracting consumers to return the PV equipment after its end of life (Salim et al., 2019).

Therefore, the challenges of recycling are related to the need to (i) increase the recycling units, (ii) simplify the collection-transportation scheme, and (iii) ensure the operational viability of recycling activities on a large scale (Tsanakas et al., 2019).

4.2.6 Legitimation

According to Bergek et al. (2008), in order to have legitimacy, new technology needs to comply with important legislation and standards and needs to be socially accepted and desirable by actors. This is important to mobilize resources, to form demand, and basically to form new industries.

Alignment with legislation and social acceptance

Through the numbers reported by Eurostat (the European Statistical Office) regarding the number of PV panels waste collected, recovered and prepared for reused and recycling[5], it is possible to have an idea about the alignment of the TIS with the targets established in the WEEE Directive. Table 4-4 shows the numbers reported by selected European countries:

Table 4-4 – Compliance with the PV waste targets of WEEE Directive

Reported data - Year 2018					**Targets WEEE Directive for PV**
PV waste management approach	**Germany**	**France**	**Italy**	**Hungary**	
Number collected (tons)	7865	1555	1350	2289	

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[5] The last year available in Eurostat is 2018 (date checked: 11/05/2021)

Number prepared for reused and recycled (tons)	6896	1399	1361	1890	
Number recovered (tons)	7708	1513	1408	1890	
% prepared for reused and recycled	88%	90%	101%	83%	80%
% recovered	98%	97%	104%	83%	85%

Source: Based on Eurostat (2021).

Although it is possible to conclude that, based on the data available, Germany, France, Italy, and Hungary comply with the targets established in the WEEE Directive for PV waste (except for the percentage recovered in Hungary), it is not possible to confirm if the whole Europe complies with those targets, once only a few countries have reported relevant data to Eurostat. Furthermore, there is a lack of standards mainly for reusing activities, as also pointed out in section 4.2.5.1. For the ecodesign activities, the legislation is under development, as also mentioned previously in section 4.2.5.1.

Value base in industry and society and influences

Although the awareness of the general population regarding PV waste and the importance of addressing CE initiatives is low, some actions are being carried out by the government, universities, research centres, associations, and companies of the sector that contribute to the legitimation of the TIS. Based on the interviews conducted, those initiatives are research and experiments (examples of projects, new entrants and technologies in section 4.2.2), funding (The Horizon 2020), new technologies (the NICE technology, for instance), legislation development (Ecodesign legislation and Energy label), policies recommendations (one of Circusol's tasks and ecodesign study performed by European Commission), group discussions (Solar Power Europe group discussion, IEA Force Task 12) and CE initiatives (companies examples mentioned in section 4.2.4).

Furthermore, regarding advocacy coalitions that can influence legitimacy, one of the interviewees mentioned a group of actors involving the German NGO Deutsche Umwelthilfe, First Solar, Veolia, the take-back scheme company for electronics take-e-way, and Rosi Solar, a recycling company. In 2021, together, they collaboratively launched a white paper about challenges and opportunities to the circularity of photovoltaics to push towards more stringent regulations when it comes to the exportation of PV panels and more precise definitions of what needs to be recovered based on the environmental footprint (R9). Another example of an advocacy coalition is the European Raw Materials Alliance (Erma), launched in September 2020, which aims to reduce the European dependency on raw materials through a circular economy approach, innovation, and green products. The alliance includes companies, society, NGOs, government, among others (ERMA, n.d.). At last, the same interviewee (R9) pointed out a report released by a consortium group called CEWASTE that strongly recommends rules for recycling high-value raw materials. Funded by the Horizon 2020 program, the CEWASTE consortium of nine partners aims to develop a voluntary certification scheme for collecting, transporting, and recycling valuable and rare materials from WEEE and batteries (CEWASTE, n.d.).

4.2.7 Development of external economies

According to Bergek et al. (2008), positive external economies are relevant to the development and growth of a TIS and can be used to measure the positive dynamics of the other six functions. New entrants are important to the development of positive externalities whose examples are: opportunities, pooled labour markets, specialized companies, resolution of uncertain situations and flow of information and knowledge (Bergek et al., 2008).

External economies are weakly developed. This is because there are few new entrants, as seen in section 4.2.2, as well as few companies exclusively focused on circular economy strategies, as seen in section 4.2.4. Furthermore, the number of specialized companies is also low.

Through the analysis of the six functions, however, it is possible to see some initial positive externalities resulting from the dynamics between them, such as (i) the Horizon 2020 program funding enabling experiments, which contributes to knowledge development, legitimation and market formation; (ii) networks such as Task 12 from IEA-PVPS and Solar Photovoltaics project from EC, contributing to knowledge development, raising awareness among the population and policymakers and to the creation of potential ecodesign legislation.

5 Discussion

This chapter has three aims: (i) to interpret the findings and results presented in the previous Chapter, connecting them with the research questions (section 5.1); (ii) to show the importance of this thesis through its contributions and (iii) to present general reflections about legitimacy, generalizability and limitations of the thesis (section 5.2).

5.1 Interpretation of the findings and results

The interpretation of the findings and results is presented in three subsections:

- Subsection 5.1.1: represents step four of the adapted TIS framework (as mentioned in section 3.1), with the assessment of the seven functions and the system as a whole, addressing RQ1.

- Subsection 5.1.2: illustrates step five of the TIS framework, with the summary of the drivers and barriers to a transition to a circular economy in the solar sector. It addresses RQ2 (barriers) and part of RQ3 (drivers).

- Subsection 5.1.3: establishes key policy issues, goals and opportunities, representing step six of the adapted TIS framework, as well as the other part of RQ3 (key policy issues, goals and opportunities).

5.1.1 Assessing functionality

According to Bergek et al. (2008), after identifying the seven key functions of the TIS, the next step is to evaluate how the TIS is behaving and performing. One way to do this analysis is to check first the phase of development of the TIS, which can be either formative or growth and then to what extent the functions are currently filled in that TIS phase. The characteristics of a formative phase are usually uncertainties regarding technologies and markets, a formative period shorter than ten years, not well-established product prices, not articulated demand, etc.

Based on the results presented in the previous chapter, an assessment of the structural components and the functions of the TIS European Circular PV Innovation System was carried out and is presented below.

Regarding the **actors and networks**, it is possible to verify that an increasing number of actors started to engage in the circular economy system and can be found across the whole PV value chain. However, the number is relatively small. Moreover, few companies, associations and networks are dedicated exclusively to the CE activities in the solar sector in Europe. It is also possible to conclude that collaboration and sharing of information between them is very important for these strategies to occur, as indicated by many interviewees and authors, as mentioned in section 4.2.3.

The number of ongoing **experiments** connected to CE strategies in the solar industry, including new technologies (NICE from Appolon Solar) and entrants (ELSi and Frelp by Sun), is also low. All of them received fund from the Horizon 2020 program, which is the main source of **investments** being made in projects related to recycling, reuse and ecodesign technologies, business models and strategies. These investments represent about 74 million euro in projects from 2015 to 2024. Regarding **human resources**, the sum of the number of people working with CE initiatives in the interviewed organizations, taking into account the highest numbers reported by them, would be approximately 550 people. This number is extremely low compared to the 3.8 million jobs in the solar PV industry worldwide (IRENA, 2020a).

On the other hand, the **development of knowledge** in this area has been increasing in recent years, especially in the last decade. This can be confirmed through the number of publications that have increased drastically from 2005 to 2020. The **level of awareness** of the public, policy-makers and companies related to the importance of CE strategies in the solar sector is growing, although it is still considered low in general. In that sense, the most mentioned **missing skill** pointed out by the interviewees, i.e. the education/lobbing and communication, is directly connected to this level of awareness. Therefore, to increase the current level of awareness, more education, lobbying and communication is needed.

There are many factors that **influence and drive organizations** and networks to work with CE initiatives in the solar sector. One of them, indicated by interviewees and scholars, is the pressure from a political/**institutional** side, which occurs through laws such as the WEEE Directive. This Directive is the main legislation in place that establishes specific targets for PV panels waste, incentivizing recycling and reuse and encouraging ecodesign of PV panels. However, it is not possible to know, based on Eurostat data, if the targets are being met or not by all the European countries because only a few of them are disclosing this information. The countries responsible for the most significant amounts comply with the law. In addition to that, some improvements to this legislation, pointed out by the interviewees, would contribute to the development of the TIS, such as (i) the establishment of specific targets for recycling of high-value materials, (ii) the definition of the waste as a product in order to reduce the limitations of transportation between countries, and (iii) the financial incentive to recycling, reuse and ecodesign activities. Regarding ecodesign strategies, it is expected that the potential new regulations that are being discussed by the European Commission establish those incentives as well as specific requirements for ecodesign and energy label.

Other **drivers** mentioned by the majority of the interviewees were (i) the potential for recovery of raw materials, (ii) the growing generation of PV waste and (iii) the external dependency on raw materials and PV modules. The same aspects are also mentioned by many scholars and institutes, as mentioned in section 4.2.1. In addition, they are aligned with the New Circular Economy Plan, another key policy. Some of these aspects, especially items (i) and (iii), were also the main motivation to **advocacy groups** acting in the area (NGO Deutsche Umwelthlife, ERMA and CEWASTE), who are advocating for better policies regarding those matters.

About **market formation**, in general, there is a low demand for ecodesigned and reused PV panels and recycled materials, and presently only a few companies exclusively work with CE strategies. The ones working with recycling and ecodesign are usually somehow connected to the producers, whereas the ones working with reused PV panels are more independent. Furthermore, there are institutional stimuli mainly for recycling and reuse (with some improvements needed, as mentioned earlier in this section) since the regulations for ecodesign are under discussion. Basically, the main barriers to the market development of ecodesigned and reused PV panels, as well as recycled materials, are (i) the long lifetime of PV panels, which makes it difficult for companies to be able to have long-term thinking to plan and invest in actions of the circular economy; (ii) the lack of guarantee of material supply, due to the low quantity of waste of PV panels, especially for recycling and reuse market; (iii) lack of specific target for recycling of high-value raw materials; and (iv) lack of trust regarding reused PV panels, due to the lack of proven guarantee of its performance and quality. Therefore, based on the information collected about the product users, the purchase processes, the demand profile and institutional stimuli, it can be concluded that the market of the TIS in focus is on the nursing phase.

Despite the barriers, there are activities being performed by the actors and networks that contribute to **positive externalities** and consequently to the **legitimation** of the TIS in focus, such as research, funding programs, experiments, discussion of laws, etc. At last, there are some opportunities foreseen that will contribute to TIS development, resulting from when there is a higher amount of waste and when the new ecodesign regulation is in effect. Some examples are job creation, automation of collection and separation of waste and internal market for recovered materials, reused and ecodesigned PV panels.

Based on the analysis above, it is possible to say that some functions are more developed than others. For instance, the function Influence on the Direction of Search presents clear and robust drivers, whereas the Market Formation function presents several weaknesses such as low demand, low institutional stimuli, etc. Another example of a function whose level of strength is higher is the Knowledge Development function, with a significant increase in terms of publications, as well as knowledge being generated by experiments, projects, R&D, companies, etc. In addition, the Resource Mobilization function, although investments are being made, the number of people working with CE is low, and there are several skills to be developed and /or improved. The function Entrepreneurial Experiments also present a low number of projects, as mentioned previously. About the Legitimation function, despite having some initiatives as well as some advocacy groups, the level of awareness of the public, in general, is low, contributing to a decrease in the legitimation of the CE strategies in the sector. At last, positive external economies need to be further developed. Table 5-1 shows the level of strength for each TIS function:

Table 5-1 Level of the strength of the TIS functions.

TIS Function	**Level of strength (high, medium, low, super low)**
Influence on the Direction of Search	High
Entrepreneurial Experimentation	Low
Resource Mobilization	Medium
Knowledge Development	High
Market Formation	Super low
Legitimation	Low
Development of External Economies	Low

Source: own elaboration

Therefore, in general, regarding the analysis of the system as a whole, the TIS European Circular PV Innovation System is in its **formative phase**.

5.1.2 Drivers and barriers

This section provides a structured overview of all the drivers and barriers identified in the European Circular PV Innovation System. The drivers are the aspects that influence organizations to work with CE strategies. The barriers are the aspects that block the development of the functions of the TIS, making the transition to the circular economy more challenging.

About the drivers listed in section 4.2.1, there are basically ten key factors that influence organizations to work with CE strategies in the solar sector: 1) the growing demand for solar energy technology and 2) the consequent growing generation of PV waste. 3) The projections regarding the growing volume, presented by the IRENA study in 2016, contributed to increasing awareness about the issue. There has been pressure from the political side through the WEEE Directive and the ecodesign study. For solar firms, especially those working with ecodesign, the drivers are 4) cost reduction due to the elimination of costs linked to logistics and raw material importation, as well as 5) product differentiation strategy among other companies. For companies working with reuse/repair strategies, 6) there is a strong demand for outdated modules to keep existing installations running and to repair them punctually. For organizations in the solar industry, 7) the existence of European funding programs, such as Horizon 2020, as well as 8) the opportunity to contribute to a positive environmental footprint and a truly sustainable energy technology are also key drivers. At last, for the majority of the interviewees 9) the possibility of recovering raw materials and 10) the consequent reduction of dependence on the external supply chain are the most relevant drivers.

Regarding the barriers, Table 5-2 lists the ones stated in sections 4.1.3, 4.2.3, 4.2.5 and 4.2.6, classifying them according to the type of CE strategy and TIS function:

Table 5-2 Barriers identified in the European Circular PV Innovation System

No.	Barriers	CE strategy	TIS function
1	Lack of supply/low quantity of waste	Recycling/reuse	Market Formation
2	Lack of specific target for recycling of high-value raw materials	Recycling	Market Formation
3	Informality of reused PV panels market	Reuse	Market Formation
4	Low market demand regarding ecodesigned, reused and recycled PV panels	All	Market Formation
5	Environmental issues associated with the recycling process (use of chemicals)	Recycling	Market Formation
6	Lack of economic viability to recycle due to several reasons (small amount of waste, high cost, lack of profitability)	Recycling	Market Formation
7	Lack of guarantee of performance, quality and safety of reused PV panels	Reuse	Legitimation/Market Formation

8	Lack of check about the functionality of the exported reused PV panels	reuse	Legitimation/Market Formation
9	Waste not to be considered a product	Recycling/reuse	Legitimation/Market Formation
10	Low level of awareness of the population	All	Legitimation/Market Formation
11	Lack of data about some countries in Eurostat to check the compliance with the WEEE Directive's targets	Recycling/reuse	Legitimation
12	Lack of ambition, long-term and circular strategic thinking (long lifetime of PV panels)	All	Resource mobilization/Market Formation
13	Low level of education/lobbing/communication about CE strategies benefits and waste as a resource	All	Resource mobilization/Market Formation
14	Lack of collaboration and information sharing throughout the supply chain	All	Resource mobilization/Market Formation

Source: Own elaboration based on literature review and interviews

The barriers 12 to 14, listed originally as Resource Mobilization barriers (as per section 4.2.3), were reclassified as "Resource Mobilization/Market" because the author of this thesis considered that the lack of those skills affects the decision-making of the leaders of the different organizations in the market. Furthermore, barrier 10, listed originally as an Institution barrier, was reclassified as "Legitimation/Market formation" since the low level of awareness about the importance of CE strategies can affect the legitimation of the system, as well as the market formation.

Furthermore, it is possible to see that from the 14 barriers identified, six are related to the Market Formation function, three are connected to the functions Resource Mobilization/Market Formation, one is related to Legitimation and four to Legitimation/Market Formation. Therefore, it is evident that the Market Formation function is the one that needs more improvement.

5.1.3 Key policy issues, goals and opportunities

According to Bergek et al. (2008), after analysing the system's performance, its development phase, and the drivers and barriers, the key policy issues can be identified. Furthermore, for a TIS to achieve higher development and performance, process goals can be established. Examples of process goals are to increase knowledge or enhance the market development.

Therefore, key policy issues connected to some of the barriers mentioned in the previous section were elaborated to be considered by policymakers. Furthermore, process goals linked to the key policy issues were identified. The key policy issues and the process goals are presented in Table 5-4:

Table 5-3 Key policy issues and process goals to the TIS European Circular PV Innovation System

Barriers	**Key policy issues to be considered**	**Process goals**
Low market demand regarding ecodesigned and reused PV panels and recycled materials	**Group 1** Establishment of financial incentives, such as: - Green Public Procurement, including CE criteria in contracts. - Subsidies for recycling facilities. Establishment of the informative instrument, such as: - Ecolabel: incentivize the use of the EPEAT ecolabel or create a European one.	**Enhance Market Formation**
Lack of economic viability to recycle due to several reasons (small amount of waste, high cost, lack of profitability)		
Lack of specific target for recycling of high-value raw materials	**Group 2** Establishment and inclusion of specific targets for recycling of high-value raw materials in the WEEE Directive.	
Lack of guarantee of performance, quality and safety of reused PV panels	**Group 3** Creation of standard to test/check reused PV panels, imposing minimum quality, performance and safety testing criteria.	
The informality of reused PV panels market	**Group 4** Establishment and inclusion of specific targets for reuse in the WEEE Directive.	
Lack of collaboration and information sharing throughout the supply chain	**Group 5** Prioritization and increase of funding that bring different value chain actors together, with the requirement to engage non-European suppliers.	**Enhance Resource Mobilization and Market Formation**
Lack of ambition, long-term and circular strategic thinking (long lifetime of PV panels)	**Group 6** - Stimulation of training programs through funding with the requirement to train the public and companies' employees. - Establishment of public awareness initiatives. - Creation of environmental awards for best practices regarding CE	
Low level of education/lobbing/communication about CE strategies benefits and about waste as a resource		

Low level of awareness of the population	strategies (recognizes and rewards efforts).	**Enhance Legitimation and Market Formation**

Source: Own elaboration

The key policy issues were indicated for nine out of 14 barriers. The other five were not included because the author considered that further information was necessary to establish a recommendation. The six groups of recommendations are described below:

- **Group 1** – One opportunity to enable competitiveness for nursing markets would be to establish financial incentives. Therefore, including circular economy requirements in public contracts (GPP), providing extra points for those who present ecodesign panels that are manufactured using recycled materials or are designed for reusability and recyclability. Moreover, subsidies to recycling facilities, including those that recover high-value materials, can help ensure their operational viability on a large scale, reducing costs and increasing profitability. At last, incentivizing the EPEAT ecolabel or developing a European one will likely encourage the demand for those products. However, it is important to highlight that more study must be made about the types of incentives and which one should be work better in the European context.

- **Group 2 –** The inclusion of specific targets for recycling high-value materials in the legislation will probably increase the development of new technologies and scale up the initiatives tested in laboratories.

- **Group 3 –** The creation of standards to test the quality, performance, safety and functionality of PV panels that will be reused is likely to increase the trust in this type of market, decreasing the risk of exporting PV panels that are not functioning to other countries[6].

- **Group 4 –** The WEEE Directive establishes the target related to the preparation to reuse and recycling of PV panels. However, it does not specify the target for each one of the strategies. Therefore, defining and including specific targets for the reuse of PV panels in the WEEE Directive will probably help to make this market more formal and reliable.

- **Group 5 –** Collaboration and cooperation are very important aspects to enable a circular economy, as pointed out by the literature review and interviewees. Therefore, if more funding is provided to relevant research and cooperation projects that bring different value chain actors together (similar to Circusol and Cabriss), this can lead to more collaboration in the supply chain, especially if it includes requirements to engage non-European actors.

- **Group 6 –** The lack of skills for professionals in organizations, the low awareness of the public, and the deficiency in communication about the importance of strategies of ecodesign, reuse and recycling of the PV panels, could be probably improved through

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[6] The creation of a standard for reused PV panels is one of Circusol's deliverables but has not been implemented yet.

a conjunction of actions. These are training programs incentivized through funds, environmental awards and public awareness initiatives. An example of the last one is workshops to teach people how to repair a PV panel and reused it in their houses.

The key policy issues and goals suggested above aim to improve the development and dynamic of the system as a whole, enhancing positive externalities and helping the PV sector become more circular. With that, opportunities and advantages can emerge, which are:

- Creation of jobs, as mentioned by some articles and press-release:

"The re-use of PV modules clearly creates employment opportunities for technically skilled and local workforce both in the decommissioning and the re-installation countries. This should be accompanied by proper training of the workforce, which could lead to the creation of 63 jobs per 1000 tons of electric and electronic waste according to an estimation of the RRE-USE network". (PV Cycle & IMEC, 2021).

"Enabling EoL management of PV panels (…) presents a significant opportunity for employment growth. Thus, the uptake maybe driven by the government's aim to increase the number of jobs and enhance skilled labour in local resource recovery sectors." (Salim et al., 2019).

- Creation of an internal market for recovered materials and reused panels, reducing the dependence of raw materials on the external supply chain and reducing the costs with logistic and production.

- Reduction of risk of pollution due to the minimization of waste and increase of recovered materials.

- Enabling the automation and consequent optimization of tasks such as collection, segregation and test, as mentioned by one of the interviewees:

  "(…) a bigger size of the market would certainly help because one could see opportunities for economies of scale, for example, the entire logistics of disassembling, the sorting and the collection. (…) once there will be larger quantities, one could optimize, automate, for example, certain processors. One could automate certain testing procedures. The entire logistics system would become more efficient." (R6).

5.2 The significance of this research and general reflections

Comparing the knowledge stated in Chapter 1 of this thesis about the problem of PV panels waste and the importance of circular economy strategies to the results obtained and presented in Chapter 4, it is possible to realize that this thesis enabled new visions and understandings about the subject. The main contribution is the systemic view of the status of the strategies of ecodesign, recycling and reuse, addressing other aspects not much covered before by literature, such as market, policies, investments, experiments, human resources, etc.

Another contribution is the practical and multidisciplinary view provided by actors from different organizations about the routine and challenges of working with CE strategies in the solar sector. It was also possible to see that many of the views converge with each other and that of scholars.

Furthermore, other contributions of this thesis are related to the use of the TIS framework. **First**, the TIS was chosen due to the lack of a systematic approach to the existent circular economy indicators, as stated in section 2.4. The majority of approaches focus on waste management and do not consider other themes. In addition to that, many tools and frameworks are aimed at companies and some at cities/regions, but a sector approach has been lacking so far. Therefore, the TIS approach was a suitable framework to meet the goals of this thesis, filling the gap of a framework to assess CE initiatives that have both system and sector attributes. **Second**, using the TIS framework in the circular economy context is novel, being even more innovative in its use in the solar photovoltaic sector. Its application in this thesis worked well because (i) the ecodesign, reuse and recycling strategies to some extent also have technological innovation aspects; (ii) the dynamics and cooperation between actors are important for the development of both the TIS and the CE strategies; and (iii) through the use of the framework, it was possible to make a diagnosis of the status of the CE strategies, as well as of the barriers that impede a transition towards a circular economy. **Third**, the use of the TIS framework for the analysis of CE strategies also contributes to the framework itself, in the sense that it expands its use to other contexts. Another contribution to the framework was made through an adaptation needed for the thesis, as already mentioned in section 3.1, referring to the change of focus of the object to be analysed, from products to processes.

The findings of this thesis are specific to the solar photovoltaic sector in Europe. However, it could be partially used by the wind power sector since waste issues are similar to the solar industry, with respect to the composition of the wind turbines containing valuable materials. Furthermore, the results might be of value of regions outside Europe. In addition, the TIS framework can, with some adaptations, be used to study the circular economy of other sectors and perhaps of cities and companies.

About the limitations of this research, the author identified two of them connected to the TIS framework. First, the framework has suggested some indicators for each function, and due to the formative phase of the European Circular PV Innovation System, not all the indicators could be fully identified. Second, another limitation was the focus of the TIS in Europe, considering that sometimes it is difficult to exclude the influence of other countries due to the interconnectivity characteristic of the PV panels value chain.

6 Conclusion

This chapter presents a summary of the thesis (section 6.1) as well as recommendations for policymakers and future research (section 6.2).

6.1 Summary

The increase in solar energy installation in the world, despite being in line with the main guidelines and agreements to combat climate change, can have negative consequences for the environment and economy linked to the generation of waste from PV panels. The prediction of a significant increase in such waste from 2030 raises concern due to the hazardous and valuable components of these PV panels, which may result in the risk of pollution and wastage of rare resources, respectively. In view of this, this thesis proposed to understand what Europe has been doing to prepare for this scenario, as well as to avoid the generation of waste. Since the study suggests that circular economy can be a solution to this challenge, specifically ecodesign, reuse and recycling strategies, the objective of this thesis was also to understand what are the actions that make organizations work with these strategies (drivers), as well as barriers to the transition to a circular economy in the solar sector. Finally, the research aimed to identify how the solar sector in Europe could become more circular, identifying key policy issues based on the identified barriers and identifying goals and opportunities. To this end, the author proposed and answered the following research questions:

> *RQ1: What is the state of the art on the circularity of the PV sector in Europe?*
>
> *RQ2: Why is the PV sector in Europe not yet circular yet?*
>
> *RQ3: How could the PV sector in Europe become more circular?*

The answers to these questions were based on 12 interviews, three webinars and around 60 articles and reports, as well as magazine news and companies' websites. In addition, the TIS framework was used as a guide for data collection and interviews, as well as for presenting the results. This framework has six steps, which were slightly adapted to this thesis, consisting of (1) defining the TIS (object of study), (2) identifying the components of the system that influence its development and performance, that is, the actors, networks and institutions (policies, laws and culture), (3) identifying the status of 7 key functions that also influence system performance and development (knowledge development, market formation, resource mobilization, entrepreneurial experimentation, development of external economies, influence on the direction of search and legitimation), (4) analyzing the functionality of the system, (5) pointing out barriers and drivers and (6) identifying key policy issues, goals and opportunities. Thus, it was assumed that the system studied is the European Circular PV Innovation System, having as its object the circular economy strategies of ecodesign, reuse and recycling. In addition, steps two, three and four guided the response to RQ1, step five provided answer to RQ2 and part of the RQ3, and step six assisted in responding to the other part of RQ3.

The thesis managed to answer the three research questions, and the main conclusions are:

(RQ1) The results indicate that circularity activities exist in the PV sector in Europe. However, the European Circular PV Innovation System is so far only in its formative phase, with many obstacles towards a more complete transition to a circular economy yet to be overcome. In general, investments in research projects and experiments are occurring through the Horizon 2020 funding program. This has helped to involve many actors through the solar value chain, to establish networks and advocacy coalitions, and to increase the knowledge base on circularity in the PV sector. However, although legislation is partially in place (with some further policies under discussion), only few organizations are exclusively dedicated to circular PV. Also, the level of interactions and collaborations between them is relatively limited. Furthermore, the market for reused and ecodesigned PV panels and recycled materials is not very well-formed, with some uncertainties and informalities and low demand regarding recycled materials, as well as eco-designed and reused PV panels. Therefore, some functions of the innovation system are more developed than others, the Market Formation function being the one that needs most improvement.

(RQ2) The findings presented the barriers that are blocking the solar sector to become circular. Many barriers were identified, with the majority being related to market development (such as lack of supply guarantee due to the low quantity of waste; low market demand; high cost of recycling, lack of specific targets in the legislation), confirming that it is the weakest function of the European Circular PV Innovation System. Other barriers were related to resource mobilization (lack of long-term and circular strategic thinking; lack of collaboration) and legitimation (low awareness about the importance of the CE strategies).

(RQ3) To answer this question, the drivers, key policies, goals and opportunities were identified. About the drivers, the main aspects that lead organizations to work with CE strategies are related to the necessity to deal with the increasing generation of waste, to the possibility of recovering valuable materials, reducing costs, and finally to the consequent likelihood of becoming less dependent of the external supply chain. In order to further enable a circular transition in the PV sector, policymakers need to foremost focus on enhancing market development, resource mobilization (human resources skills) and legitimation. Finally, the opportunities and advantages of having a more circular PV sector are related to job creation, reduction of risk of pollution, and the establishment of an internal market for recovered materials, etc.

The systemic approach was fundamental to provide a holistic view of the status of CE strategies, filling a gap in the area of study. In addition, the analysis of the seven functions of the framework expanded the themes analyzed compared to the literature.

Thus, this thesis contributes to the discussion of the circular economy in the solar sector. In addition, it contributes to increasing the circularity of the PV sector in Europe through the key policies and opportunities indicated. Finally, there is an academic contribution due to the use of the TIS framework in an innovative way in the context of circular economy in the solar sector.

6.2 Recommendations for policymakers and for future research

To enable a transition to a circular economy by strengthening eco-design, reuse and recycling initiatives, this thesis encourages policymakers to consider different policy approaches, such as financial incentives (subsidies, green public procurement), standards, ecolabels, and specific targets on legislation, as well as awareness raising initiatives.

In addition, there are some opportunities for further research. Firstly, given that the IRENA projections about the generation of PV waste are from 2016, future research could make updated and more accurate projections about how and when the PV waste volume is going to grow under different scenarios. This would give market actors more information and trust about when they need to be prepared for this PV waste, planning initiatives to manage it taking into account circular economy strategies.

Secondly, this thesis focused on the CE strategies (ecodesign, reuse and recycling) as the main object of the TIS analysis. Further research could consider circular business models as the object of study, given that they are considered important to promote the transition towards CE (Salim et al., 2019; Strupeit & Bocken, 2019). Some examples of the circular business model are product-service system (PSS), industrial symbiosis and sharing platforms (Nußholz, 2017).

Thirdly, further research could compare the results of this thesis (such as resources invested, number of publications, number of organizations, barriers, etc.) to the results of other similar systems to assess the TIS's performance and development from a different perspective. In addition, performing the same analysis of this research ten years from now would also provide interesting information about the status of the system, enabling the comparison of the findings of this thesis and the assessment about how the system has developed during the years, what changed, if barriers were solved or new ones were created, whether the policy recommendations were implemented, among other factors.

At last, considering that the key policies indicated by this thesis are opportunities for policy interventions, more investigation and study is needed to analyse which type of financial incentives would work better in the European context.

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Appendix 1 – List of interviewees

Institution/company	Code for in-text reference	Position	Organization type in this thesis context	Date of interview	Country
SolarPower Europe	R1	Senior policy and market analyst	Association - organizations representative	22/03/2021	Belgium, but represents all European countries
PV Cycle	R2	Managing Director	Association - collecting scheme	02/04/2021	Belgium (headquarter) with representatives in most European countries
European Commission/DG GROW	R3	Policy Officer	Government - policymaker	12/04/2021	Belgium
Fraunhofer Institute for Solar Energy Systems ISE	R5	Business Developer Service Life & Sustainability	Research institute	15/04/2021	Germany
Circusol	R6	Researcher	Research consortium H2020 project	19/03/2021	8 European countries
Appolon Solar	R7	Director Operations, R&D	Manufacturer	13/04/2021	France
Solitek	R8	Project Manager	Manufacturer	13/04/2021	Lithuania
First Solar	R9	Global Sustainability Director	Recycling facility	11/12/2020 and 08/04/2021	Germany
SunCrafter	R10	CEO	Refurbish and reuse company	11/12/2020 and 12/04/21	Germany
DSM	R11	Market Insights and Sustainability Lead	Manufacturer	08/04/2021	The Netherlands

pvXchange	R12	CEO	Replacement modules and spare parts and repairing company.	By email	Germany
FRELP BY SUN	R13	Technical Director	Recycling company	13/04/2021	Italy

Appendix 2 – List of webinars

Name	Date	Organized by	Subjects	Link
Photovoltaics: towards a sustainable industry	9 to 11 March	INES (Institut National de L´energie Solaire) and CEA (The Commission for Atomic Energy and Alternative Energies)	LCA; policies, legislation, ecodesign, quality&reliability, waste management, circular strategies.	https://www.ines-solaire.org/agenda/workshop-ecopv2021/
Circular Solar	1 April	Energy Academy Europe	The future of solar energy and the importance to create a circular system	https://energyacademy.org/calendar/circular-solar/
Stakeholder Webinar: Follow up study on Photovoltaic products- ongoing work on potential Ecodesign and Energy Labelling measures	29 April	European Commission	Requirement suggestions for the potential Ecodesign and Energy Labelling Directives	https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/462/documents

Appendix 3 – Questionnaire used for interview

What is the role of the institution/company related to the circularity of PV panels? What are the activities currently being performed/developed by your institution to contribute to the legitimation of the circularity of the PV sector (NETWORK; LEGITIMATION)?

Why is the institution/company engaged with this subject? What factor has led/influenced the institution to work with it? (INFLUENCE ON THE DIRECTION OF THE SEARCH)

How many people working with circular economy exist nowadays in the institution/company? Are you missing any skills to develop circular economy actions/studies in your company? (RESOURCE MOBILIZATION)?

Regarding PV ecodesign, recycling and reuse, are there any current actions being developed by other actors you are aware of? Example: research, technology, workgroup, networks, articulation of interest, experiments (KNOWLEDGEMNT DEVELOPMENT; (INFLUENCE ON THE DIRECTION OF THE SEARCH; ENTREPRENEURIAL EXPERIMENTATION; NETWORKS)

Do you know how many companies are working with ecodesign, reuse and recycling in Europe (ACTORS)?

What is the current awareness of the population, policymakers, manufacturers, importers, and installers about the importance of the PV sector's circularity? (INSTITUTIONS)

One of the main factors to make a transition to the circular economy is market formation. What would be needed to make it happen regarding a market for ecodesigned, reused and recycled PV panels? Who would be the users of these three products (MARKET)?

How an ideal scenario of the circular PV sector in Europe looks like (ASSESSING FUNCTIONALITY & SETTING PROCESS GOALS)? What goals would you establish?

What are the main drivers for a transition to a circular economy in the sector (INDUCEMENT AND BLOCKING MECHANISMS)?

What are the main barriers and challenges for a transition to a circular economy in the sector INDUCEMENT AND BLOCKING MECHANISMS)?