AN INTEGRATED DECISION-MAKING MODEL FOR SUSTAINABLE MANAGEMENT OF END-OF-LIFE SOLAR PHOTOVOLTAICS: A CASE STUDY OF SPAIN

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SYED MUHAMMAD ALI HAIDER RIZVI

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Approval of the Board of Graduate Programs

Prof. Dr. Cumali Sabah
Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Assoc. Prof. Dr. Ceren Ince Derogar
Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr Ali Berk Baştaş
Co-Supervisor

Prof. Dr. Murat Fahrioglu
Supervisor

Examining Committee Members

Asst. Prof. Dr. Abdullah Ekinci	Department of Civil Engineering/METU NCC	
Prof. Dr. Murat Fahrioglu	Department of Electrical and Electronics Engineering/METU NCC	
Assoc. Prof. Dr. Sahand Daneshvar	Department of Industrial Engineering/EMU	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Syed Muhammad Ali Haider, Rizvi

Signature:

ABSTRACT

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Rizvi, Syed Muhammad Ali Haider
Master of Science, Sustainable Environment and Energy Systems Program
Supervisor: Prof. Dr. Murat Fahrioglu
Co-Supervisor: Asst. Prof. Dr. Ali Berk Baştaş

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Solar photovoltaics have a finite service life, after which they are decommissioned. The volume of obsolete or end-of-life solar PVs is expected to be mammoth in future, owing to their extraordinary deployment in the past decade. The domination of a linear solar PV paradigm alongside a parabolic increase in solar PV installations makes the exacting challenges of the end-of-life management of solar PVs seem inevitable. Therefore, this research intends to draw policymakers' attention toward sustainable end-of-life options. The main contribution of this research is the provision of an integrated decision-making model which ascertains the extent of sustainability of four end-of-life solar PV management scenarios from the lens of a triple bottom line approach. The model includes a forecasting framework for two different installation periods and various waste projection scenarios. Following, it utilizes holistic methodologies such as the life cycle assessment, cost-benefit approach and social indicators for determining the environmental, economic and social sustainability impacts of the end-of-life solar PV scenarios. The devised framework is implemented as a case study (on Spain) to further increase the research's granularity. Utilizing the expert responses garnered through questionnaires, criteria weights for the three sustainability dimensions and assessment indicators are calculated and an overall sustainability score for each end-of-life scenario is derived. This research also inclusively emphasizes the drivers, enablers and barriers of sustainable end-of-life PV management to cope with the momentous volume of end-of-life solar PV in future.

Keywords: End-of-life solar PV, Sustainability, Solar photovoltaics, Triple bottom line

ÖZ

ÖMÜR SONUNDA GÜNEŞ FOTOVOLTAİĞİNİN SÜRDÜRÜLEBİLİR YÖNETİMİ İÇİN ENTEGRE KARAR VERME MODELİ: İSPANYA VAKA ÇALIŞMASI

Rizvi, Syed Muhammad Ali Haider
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri
Tez Yöneticisi: Prof. Dr. Murat Fahrioglu
Ortak Tez Yöneticisi: Dr. Öğr. Üyesi. Ali Berk Baştaş

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Solar fotovoltaik (FV) panelleri sınırlı bir hizmet ömrüne sahiptir. Eski veya ömrünü tamamlamış güneş FV leri hacmi, son on yılda artan kullanım seviyelerine paralel olarak, çok yüksek rakamlara ulaşması beklenmektedir. Şu anda hakim olan, linear kullan-at modeli ve parabolik bir şekilde artış gösteren solar FV kurulumları, etkin bir FV ömür sonu yönetimini kaçınılmaz kılmaktadır. Dolayısıyla bu araştırma, politika yapıcıların dikkatini sürdürülebilir yaşam sonu seçeneklerine çekmeyi amaçlamaktadır. Bu araştırmanın ana katkısı, dört ömür sonu solar FV yönetim şeklinin sürdürülebilirlik derecesini üç ana boyutundan (çevresel, ekonomik ve sosyal) tespit eden entegre bir karar verme modelinin tasarlanmasıdır. Model, iki farklı kurulum dönemi ve çeşitli atık projeksiyon senaryoları için bir öntahmin yöntemi ve çerçevesi içerir. Ardından, kullanım ömrü sonu güneş FV senaryolarının çevresel, ekonomik ve sosyal sürdürülebilirlik etkilerini belirlemek için yaşam döngüsü değerlendirmesi, maliyet-fayda analizi ve sosyal göstergeler gibi bütünsel metodolojileri kullanılmıştır. Araştırmadaki ayrıntı düzeyini daha da artırmak için, tasarlanan çerçeve bir vaka çalışması olarak uygulanmıştır (İspanya bölgesi üzerine).

Anketler aracılığıyla toplanan uzman yanıtları kullanılarak, üç sürdürülebilirlik boyutu ve değerlendirme göstergeleri için kriter ağırlıkları hesaplanır ve her bir yaşam sonu senaryosu için genel bir sürdürülebilirlik puanı elde edilir. Bu araştırma ayrıca, gelecekte yaşam sonu FV'lerinin yüksek hacmiyle başa çıkmak için sürdürülebilir yaşam sonu FV yönetiminin yürürlüğe konmasını kolaylaştırıcıları, olanak sağlayıcıları ve engellerini tespit etmiştir.

Anahtar Kelimeler: Ömrünü tamamlamış güneş FV, Sürdürülebilirlik, Güneş fotovoltaikleri

To Aisha and Sibgha

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter entails an overview of the background and research motivation in Section 1.2, followed by formulating research questions in Section 1.3. In light of the established research questions, research objectives and pertinent contributions to the existing literature are outlined in Section 1.4 and Section 1.5, respectively. To conclude this chapter, the thesis structure is presented in Section 1.6.

1.2 Problem discussion and motivation

The global concern regarding climate change and associated threats to the planet has been gaining momentum over the past couple of decades. Owing to this, the global leaders at the COP-26 meeting in November 2021 in Glasgow pledged to address the issue and take active and pertinent measures (van den Berg et al. 2022). According to President Biden, in light of global warming, the US intends to cut more than a giga ton of GHG emissions by 2030 and introduce tax credits on solar panel installations (Gautam et al. 2022). Such pledges and similar commitments by global leaders are instrumental for transitioning towards renewable energy technologies such as solar.

Taking into account, the targets set out in the Paris Agreement and the UN’s 2030 Agenda for sustainable development redesigning the economy via the adoption of sustainable and renewable sources of energy generation is indispensable (Rizvi et al. 2022; Vakitbilir et al. 2022). Stemming from that fact, solar PVs have become one of the fastest adopted renewable energy technologies. On account of its environmentfriendly nature (Celik et al. 2018) and abundant global solar resources, the outlook of the solar PV market advocates continual growth in the upcoming years as well (Domínguez & Geyer 2017; Santos & Alonso-García 2018). PV growth projections estimate an unprecedented adoption that shall exceed 4500 GW and represent 25 percent of the global energy mix by 2050 (IRENA 2016; Mahmoudi et al. 2020; Ganesan & Valderrama 2022).

Moving forward, this growth can be restricted by a shortage of resources and PV's operational life span of about 25 to 30 years, thereby requiring a proactive end-of-life management plan (Mahmoudi et al. 2019). Based on a study by the Fraunhofer Institute, certain raw materials utilized in solar PV manufacturing will be non-existent due to their limited availability (Gautam et al. 2021). Therefore, to ensure uninterrupted PV growth in future, availability of enough raw material, competitive cost of PV fabrication, lower pertinent environmental burdens and proper waste disposal are essential (Zhan et al. 2019). Cognizing of this fact, the developed countries in the EU, Japan, the United States and Australia have either constituted end-of-life management policies and regulations or are in the process of doing so (Domínguez & Geyer 2017; Domínguez & Geyer 2019).

Sustainable end-of-life management is not a nascent phenomenon, and there have been many efforts for circular management and recycling of end-of-life electronic items (Islam & Huda 2018). On the contrary, recycling solar PVs has majorly been overlooked due to the insufficient quantity of discarded PVs at present (Ganesan & Valderrama 2022). As a matter of fact, recycling not only ensures raw material supply in future but is also key to minimizing the environmental implications of the solar PV sector (Contreras Lisperguer et al. 2020). With the rapid increase in solar PV penetration and an absence of apt end-of-life strategies, an eventual rise in environmental burdens through landfilling is otherwise inevitable (Mahmoudi et al. 2019).

The volume of end-of-life PV in the near future has the potential to develop a nascent industrial sector that brings social, economic and obvious environmental benefits

(Santos & Alonso-García 2018; Prajapati et al. 2019). The secondary raw materials from discarded PVs can potentially fabricate 2 billion new solar PVs, translating to 15 billion dollars in value (IRENA 2016). According to projections, about 0.15 to 0.25 percent of the PVs encounter early failure, aggregating to a sizeable quantity over time (Ganesan & Valderrama 2022). Although solar PVs have a relatively long lifespan, devising innovative and sustainable end-of-life strategies is critical for effectively catering for the momentous volume of discarded PVs in future.

The PV waste stream is heterogeneous and, consequently, underpinning countries' engagement is necessary. Mahmoudi et al. (2019) suggest that a collective approach is pivotal for a shift towards sustainable management of end-of-life PV. For example, if neighbouring countries have insufficient PV waste to develop recycling or refurbishing facilities in their respective countries, there would be no incentive for them to treat the discarded PV modules. However, it could be more environmentally sustainable and economically viable if they agree to establish collective facilities.

There have been studies in recent years that focus on various aspects of end-of-life PV. Corcelli et al. (2018) included two recycling scenarios (low recovery and high recovery) and conducted a life cycle assessment. It was concluded that recycling is viable at acceptable environmental and energy costs and that the benefits from a high recovery scenario supersede the low recovery option. Latunussa et al. (2016) present a detailed life cycle assessment of the FRELP recycling project, demonstrating the associated environmental benefits through material and energy recovery. However, both these studies disregard the imperative economic aspect.

From an economic standpoint, Liu et al. (2020) determine the economic viability of PV recycling in China based on the waste generated between 2020 and 2034. The recovery cost of PV modules was 25.11 dollars per kW, whereas the unit benefit was 25.68 dollars per kW. The study concluded that the economic benefit from tax and recycled materials are the most crucial components. Faircloth et al. (2019) and Mahmoudi et al. (2020) discuss both economic and environmental aspects; however, they disregard social sustainability. Moreover, an aggregated sustainability score for each end-of-life scenario, as well as a sustainability dimension-wise score, is missing, which provides a better overall understanding to the policymakers and academicians.

Based on the relevant literature, it can be concluded that the existing literature is under a developmental phase and requires more integrated and holistic studies. Most studies have addressed a couple of aspects of end-of-life PV within a study at most, especially environmental. Viewing end-of-life PV management from a triple bottom line perspective is crucial in obtaining an overall overview of sustainability. Consequently, this research includes environmental, economic and social sustainability in addition to the forecasting mechanism.

1.3 Research questions

Predicating from the research topic discussed in the preceding sub-section, the following exploratory research inquiries are established as the underpinning of this research in the context of end-of-life solar PV:

1) RQ 1: Why is sustainable management of end-of-life PV a potential research avenue?
2) RQ 2a: How can sustainable management decisions regarding end-of-life solar PVs be made holistically?
3) RQ 2b: What are the steps required to be taken toward sustainable management of end-of-life solar PVs?
4) RQ 3: How can such a sustainable management approach framework be implemented or operationalized in a specific region?
5) RQ 4: What are the key drivers, barriers and enablers to sustainable end-of-life solar PV management?

1.4 Research objectives

Based on the problem discussion and motivation, as well as the formulated research questions, the objective of this thesis is as follows:

"Develop a holistic decision-making model, in lines with the triple bottom line, for sustainable management of end-of-life PV, with a perspective of implementing it on Spain and ascertaining the sustainability scores of the end-of-life scenarios."

Stemming from the research questions presented in the preceding sub-section, the established research objectives are as follows:

1) Evaluate sustainable end-of-life PV management as a prospective research avenue by conducting a holistic, systematic literature review and identifying the pertinent gaps in the literature.
2) Incorporate sustainability synergies from a triple bottom line perspective to develop a conceptual framework, including a waste forecasting mechanism.
3) Implement the formulated framework as a case study on Spain.
4) Collect expert responses to conduct a multi-criteria decision analysis and determine the sustainability scores for each end-of-life scenario.
5) Identify the crucial drivers, barriers and enablers to sustainable end-of-life solar PV management through responses gathered from experts.

1.5 Contributions

This research contributes to the existing literature through an entire conceptual construct that aligns with the triple bottom line approach. An integrated framework encompassing forecasting, environmental, economic and social assessment is prudently developed. Incorporating expert responses to conduct a multi-criteria decision analysis sets this research apart from the pertinent literature. Furthermore, a unique aspect of computing the sustainability score of four different end-of-life scenarios is included, which is a rarity among contemporary studies involving end-of-life solar PV. This thesis further contributes to the body of knowledge by implementing the conceptual framework in Spain, intending to encourage the policymakers and academicians to validate the framework in other regions and compare the findings with this research. In addition, expert responses on key drivers, barriers and enablers to sustainable end-of-life PV management are also summarized to identify the more relevant and conspicuous drivers, barriers and enablers.

1.6 Structure of thesis

This thesis is divided into seven discrete yet complementary chapters pertinent to the research goals. The following is a brief synopsis of each chapter:

1) Chapter 1: presents an overview of the thesis by emphasizing the research problem, formulating the research questions, and elaborating the thesis objectives, contributions and structure.
2) Chapter 2: includes a brief introduction to the fundamental concepts (e.g. sustainability, circular economy and end-of-life solar PV) and sustainable management of end-of-life solar PV as a research avenue. Further, a systematic literature review was conducted, and a holistic review of some extant studies was presented from its findings. Lastly, the research gap and scope are also provided.
3) Chapter 3: outlines the research methods and overviews the research strategies following the objectives of the thesis.
4) Chapter 4 involves developing a step-by-step decision-making model that can ascertain the sustainability of different end-of-life PV scenarios in the context of a triple bottom line.
5) Chapter 5: demonstrates the implementation of the conceptual framework as a case study. Framework application is on Spain, where the results of the forecasting, environmental, economic, social and multi-criteria decision analysis are presented.

6) Chapter 6: further elaborates on the findings of the previous chapter by comparing the outcomes with relevant studies and discussing the pertinent implications. Also, the drivers, barriers and enablers to end-of-life PVs are also outlined.
7) Chapter 7: summarizes the overall thesis, contributions to the literature and salient findings of the thesis. Also, it briefly outlines the research limitations and future research avenues.

The mapping of the chapters against the established research questions is demonstrated in Figure 1.1.

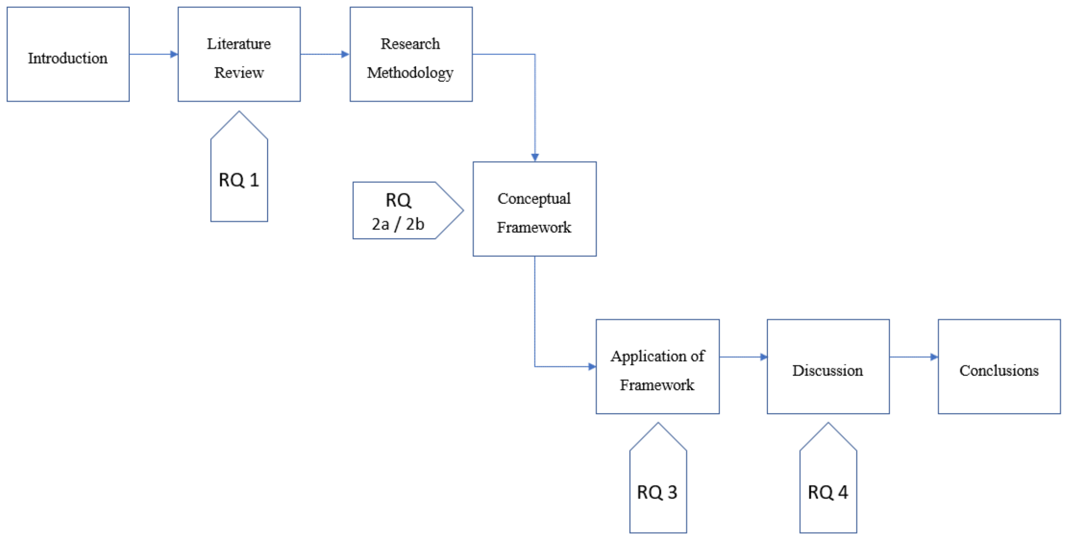

Figure 1.1. Thesis chapters and research questions

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A literature review is an inclusive and systematic approach to condensing large volumes of research that depicts the author's acquaintance pertaining to a specific field of study, including vocabulary, key theories and phenomena, along with its methods and history (Randolph 2009). Performing a comprehensive literature review also apprises the notable researchers and influential research groups pertinent to the field.

Boote & Beile (2005) highlight the importance of a dissertation's literature review by stating that a flawed literature review can be viewed as flawed dissertation because it corroborates the researcher's inability to conduct substantial research without first discerning the existing literature in the field. Therefore, writing faulty literature can be viewed as derailing a dissertation.

Resonating with the findings of Gall et al. (1996) and Hart (1998), this literature review was pivotal for the thesis in the following aspects:

- Delineating the research problem
- Rationalizing the importance of the problem
- Identifying novel lines of inquiry through recognizing existing work and research gaps
- Learning about key variables pertinent to the research topic
- Abstaining from approaches that would not fruition
- Gaining methodological acumen
- Proposing recommendations for future research,

This chapter commences with an overview of pertinent and key concepts in Section 2.2. Section 2.3 outlines the sustainable management of end-of-life solar PV as a research avenue. Moving further, a systematic literature review and its findings are outlined in Section 2.4, followed by a brief review of extant studies in Section 2.5. Lastly, a detailed emphasis on the research gaps and scope of this thesis is outlined in Section 2.6.

2.2 Overview of key concepts

2.2.1 Sustainability

Sustainability is a state in which human activity is performed in a manner that the earth's resources are conserved. It is a transformation or an optimization in human practices such that the existence of non-replaceable goods in future can be ensured (McMichael et al. 2003). With around 300 definitions of sustainability, this concept involves current and future economic development, maintenance of environment/ecosystem, and long-standing productivity of living resources (Johnston et al. 2007).

The most prevailingly accepted definition of sustainability is by the Brundtland Commission which states sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987). Initially associated with environmental concerns mainly, the terminology 'sustainable development' later was introduced. Sustainability and sustainable development are two closely linked concepts that have since been gaining popularity, especially post-2000s (Turkson et al. 2020).

Elkington introduced a triple bottom line approach in 1994 due to the prevailing dissemination of sustainability (Elkington 2013). This approach included three interconnected and mutually underpinned columns of sustainability: economic, environmental and social, also demonstrated in Figure 2.1. Since these three sustainability domains impact one another through mutual causality, the triple bottom line can be adapted to varied time horizons and contexts (Wise 2016).

There has been a significant surge in published research on ‘sustainability’ in the past two decades, to the degree that ‘sustainability science’ is often considered as a discrete field (Kajikawa et al. 2007; Schoolman et al. 2012; Turkson et al. 2020). Having said that, sustainability still has myriad interpretations based on the context. The contemporary literature not only revolves around the tripartite version of sustainability by Elkington but also discusses the United Nation Sustainability Development Goals (SDGs), which broadly speaking have the triple bottom line embedded in their goals (Purvis et al. 2019).

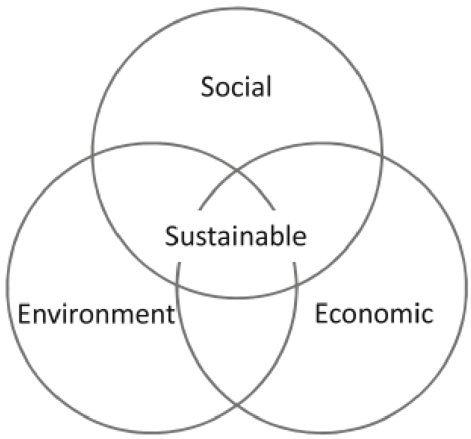

Figure 2.1. Triple bottom line concept

2.2.2 End-of-life solar PV

The term ‘end-of-life solar PV’ refers to solar panels that are no longer functional and have completed their lifetime for useful service. Solar PV reaches the end-of-life stage either in a regular or an early loss scheme. Regular loss refers to the solar PVs that have survived the average overall solar panel life span with no early attrition. Early loss, on the other hand, considers infant, mid-life or wear-out failures before the average overall solar panel life span.

With the exponential growth in solar PV installations, the number of PVs reaching the end of their lifespan will upsurge steadily (Shin et al. 2017a). Therefore, end-of-life solar PV management is essential to pre-empt and manage the volume of decommissioned solar PV in future (Chowdhury et al. 2020). Based on the waste management hierarchy, the four possible EoL scenarios entail reuse, recycling, incineration and landfill (Lunardi et al. 2018). However, the preferred and sustainable EOL options include: recycling, reusing and reducing (IRENA 2016).

Effective end-of-life solar PV management can be a pivotal component of the PV value chain. Not only will it spawn new industries, but it is also aligned with the global paradigm shift to long-term sustainable development.

2.2.3 Circular economy

There exists no clear evidence of a single originator of the concept of circular economy (CE), however, contributors include, John Lyle, Walter Stahel, Michael Braungart and William McDonough (Geissdoerfer et al. 2017). Several notable researchers like Andersen (2007), Su et al. (2013) and Ghisellini et al. (2016), widely attribute the introduction and the development of a conceptual framework of the CE concept to Pearce & Turner (1989). The principles of the circular economy mainly contain the 3Rs: reduce, reuse, recycle and the 6Rs: reduce, reuse, recycle, redesign, recover, and remanufacture.

The present-day understanding of CE and its practical applications have evolved over the years to integrate different contributions from diverse concepts that align with the viewpoint of closed loops. Some of them include cradle-to-cradle (McDonough & Braungart 2002), regenerative design (Lyle 1994) and blue economy (Geissdoerfer et al. 2017). Ellen MacArthur, whose definition of CE is the most renowned, framed it as ‘an industrial economy that is restorative or regenerative by intention and design' (Geissdoerfer et al. 2017). The circular economy concept entails that the manufactured solar PVs are built to last and in certain scenarios are repairable when they break, and recyclable at the end of their life span. It aims to close the supply chain loop by reusing and/or recycling existing materials, to minimize the need for virgin materials (Bocken et al. 2016).

The CE economy concept has been gaining momentum with policymakers and governments of the developed nations on a regional, national and international level. For example, Germany was the first to incorporate circular economy into their national laws in 1996. Japan, in 1996, followed with their 'Basic Law for Establishing a Recycling-based Society' and China, in 2002, with 'Circular Economy Promotion Law of the People's Republic of China. EU's 'Circular Economy Strategy', in 2015, is another notable step in paving the future of this concept. Moreover, CE has also received growing attention from academics such as Andersen (2007), Lieder & Rashid (2016), Wells & Seitz (2005) and Weissbrod & Bocken (2017).

Stemming from the 'take-make-waste' approach also referred to as the linear approach, necessitates extensive resources that continue to get less readily accessible. Adding loops inside the existing PV value chain could significantly minimise both the mandatory inputs and produced outputs.

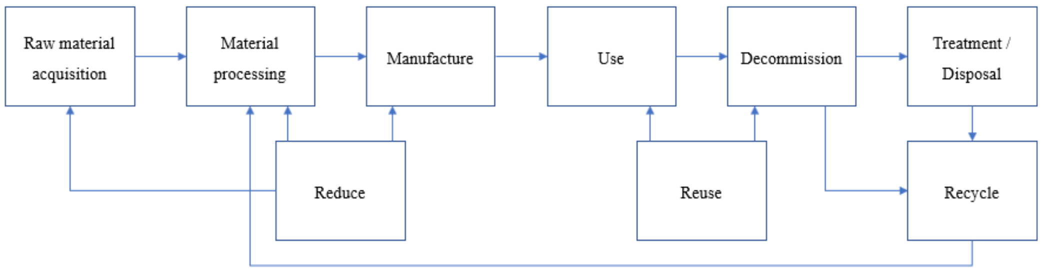

Figure 2.2. Circular solar PV approach

The circular economy paradigm, as demonstrated in Figure 2.2, would reduce the externalities alongside retaining the value during every phase of the PV supply chain, which is essential to sustainably administer the solar PV waste.

2.3 Sustainable management of end-of-life solar PV as a research avenue

There is a growing global trend of utilizing solar PV to deal with the accelerating energy demands and to protect the environment and ecosystem. The energy produced via solar PV is not only clean and inexhaustible but also indispensable for a society's sustainable development (Hosenuzzaman et al. 2015; Sher et al. 2015). However, the currently adopted linear end-of-life options, alongside, the growing incorporation of solar panels in the energy mixes, pose a sustainability concern that, if not dealt with, could be momentous in future (IRENA 2016; Chowdhury et al. 2020).

In recent years, solar PV has been a theme of numerous sustainability studies and, therefore, has established itself as a popular research topic with researchers and academicians. A vast majority of studies on solar PV revolve around the aspects pertinent to the cradle to grave (Tsang et al. 2016; Tannous et al. 2018; Sierra et al. 2020; Ludin et al. 2021). Post-life management studies, in comparison, are considerably less, mainly due to the scarcity of available data and the unreasonable amount of solar PVs reaching the decommissioning stage (Latunussa et al. 2016). On top of that, more than two-thirds of the PV end-of-life studies are conducted on a laboratory scale, corroborating the argument that this study area needs further reportage (Mahmoudi et al. 2019).

End-of-life solar PVs present significant untapped economic opportunities which can open pathways for innovation in circular management (Curtis et al. 2021; Majewski et al. 2021). Recycling or re-utilizing end-of-life solar PV can unlock invaluable components and substantial quantities of raw material that can be utilized for manufacturing new solar panels or in other sectors. Recovered materials from end-of-life solar PV is required in different industries. For example, solar PV waste glass can be utilized as a raw material in manufacturing ceramic tiles. It can enhance the desirable mechanical properties of geo-polymers (Mahmoudi et al. 2019).

Stemming from the points above, this thesis primarily emphasizes a framework through which the circular and sustainable management of post life solar PV can be promulgated to facilitate the incorporation of more sustainable end-of-life practices and policies globally.

2.4 Systematic literature review (SLR)

2.4.1 Methodology

To map and investigate the research objectives stated in the introduction, a rigorous systematic literature review was conducted by shadowing the framework offered by (Tranfield et al. 2003; Briner & Denyer 2012). Rather than opting for a generalized and a traditional literature review, a systematic literature review was preferred due to its following characteristics: enabling extensive and scientific literature perusing as well as critical identification of 'knowns' and 'unknowns' of the particular field of investigation (Briner & Denyer 2012). This inculcated a strong foundation on the subject and a thought process that eventually facilitated relevant theory constructions.

The adopted methodological framework of the systematic literature review comprised of the following phases:

1. Phase 1: Planning & Formulating the Research Objectives

To initiate with the SLR study, a preliminary step included an informal scan of the literature to identify the research objectives and outline the scope of this thesis. Furthermore, the gap in the literature was verified alongside defining the time frame and combination of keywords to be utilized in the systematic research.

2. Phases 2 & 3: Location, Selection and Evaluation

The relevant publications were located by employing the two popular online database aggregators: Web of Science and Scopus, with search terms including end-of-life solar PV, end-of-life photovoltaic, PV end-of-life management, circular management end-of-life PV, recycling PV and photovoltaic disposal. These search terms were chosen based on the review of several relevant literature reviews combined with some trial and error to find appropriate initial search terms that covered most, if not all, relevant studies.

The search was limited to articles published in peer-reviewed journals and conference proceedings in English. The timeframe for the keyword search terms was set from 2002 to 2021 because the solar PV market began to gain momentum since the start of the 2000s (Franco & Groesser 2021) and the systematic literature would effectively cover two complete decades. To justify the selection of this timeframe, an informal literature scan confirmed almost no publications before 2002.

The articles obtained from the aforementioned search terms from the database aggregators were combined in an Excel sheet to identify and eliminate the duplications. The reason for utilizing more than one database aggregator was to capture all the pertinent material from the literature. Furthermore, reference lists from the chosen articles were thoroughly examined to include additional records not detected through search results. The PRISMA flow diagram shown in Figure 2.3 demonstrates the general flow of the systematic literature review.

To ascertain whether the article is relevant to the defined scope of this thesis or not, the title and abstract were read first. The integration of sustainable management of end-of-life solar PV was the general inclusion criteria at this stage. The irrelevant articles were removed from the Excel sheet. A few reasons for classifying an article as irrelevant were content not related to the topic of the thesis, content overly technical or beyond the scope of the thesis (discussed from the perspective of other domains such as chemical engineering, electrical engineering etc.,) and restricted access.

3. Phase 4: Data Analysis

The shortlisted articles in the previous phase, were further studied thoroughly to identify and bifurcate into different categories such as, region of study, research methodology, sustainability dimensions (environmental, social, economic) etc., The articles' careful scrutiny and categorisation were then reported in the next phase for further clarity.

4. Phase 5: Reporting the Findings

Finally, post data analysis, findings were reported descriptively and analytically in the subsequent section (Section 2.4.2). Examining the extent and range of the pertinent research activity alongside, disseminating the SLR findings corroborated the initially identified research gaps and further streamlined the research objectives.

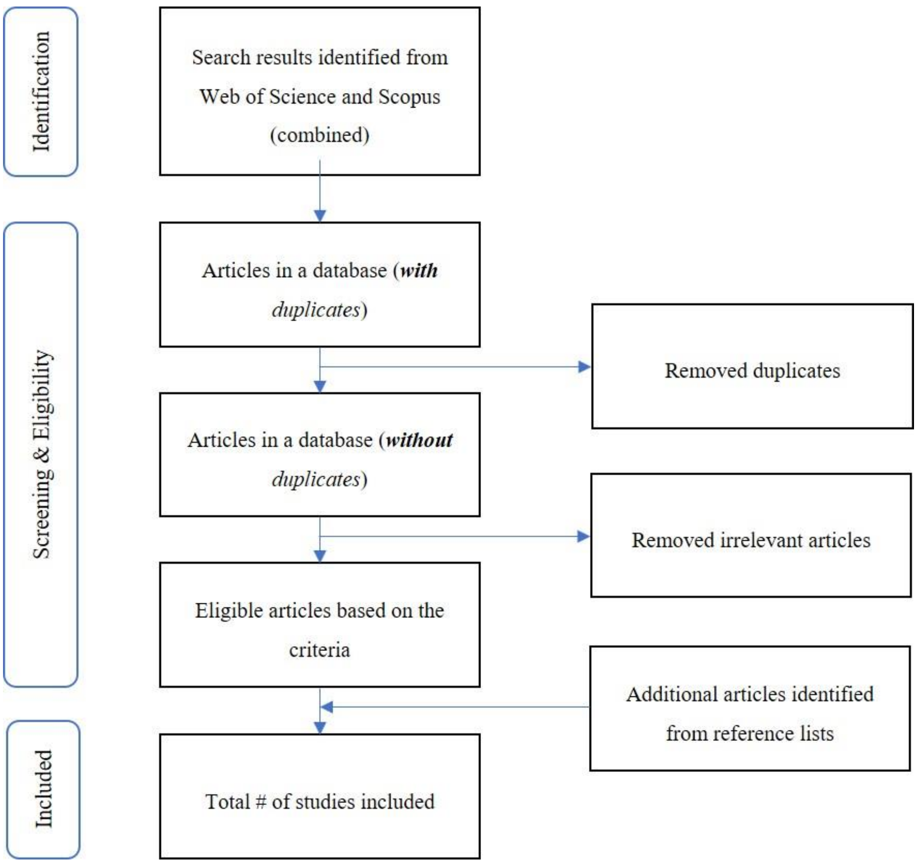

Figure 2.3. PRISMA diagram

2.4.2 Findings

The findings of the systematic literature review illustrate a growing trend in the number of published papers with end-of-life solar PV as the subject matter, especially post-2016. The number of journal articles on end-of-life PV published between 2002 and 2006 was 2. This number increased to 9 for the period 2007 to 2011. From 2012 onwards, the inclination of academicians toward the subject became noticeable when from 2012 to 2016, a total of 43 articles were published. Between 2017 and 2021, a sizeable increase of 190 percent (a total of 84 articles) compared to the previous time frame.

Figure 2.4. clearly, shows the number of published articles from 2002 to 2021. Before 2012, it can be concluded that the research in end-of-life PV was going through an incubation period, and post-2017, there was a rapid upsurge in the number of publications in this domain.

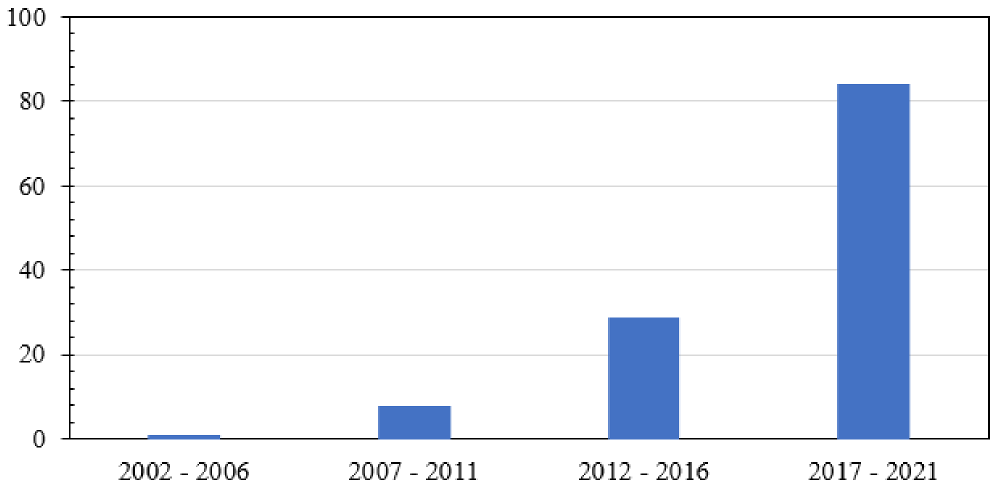

Figure 2.4. Published journal articles from 2002 to 2021

Upon comparison with the conference proceedings, Figure 2.5 demonstrates the proportion of articles published in journals was more significant (close to 85 percent). The journals with the maximum number of publications on the subject were Waste Management (13 publications), Resources Conservation and Recycling (12 publications), Solar Energy Materials and Solar Cells (11 publications), Sustainability (7 publications), Renewable and Sustainable Energy Reviews (7 publications), Journal of Cleaner Production (7 publications), Renewable Energy (7 publications), Solar Energy (5 publications) and Progress in Photovoltaics (5 publications).

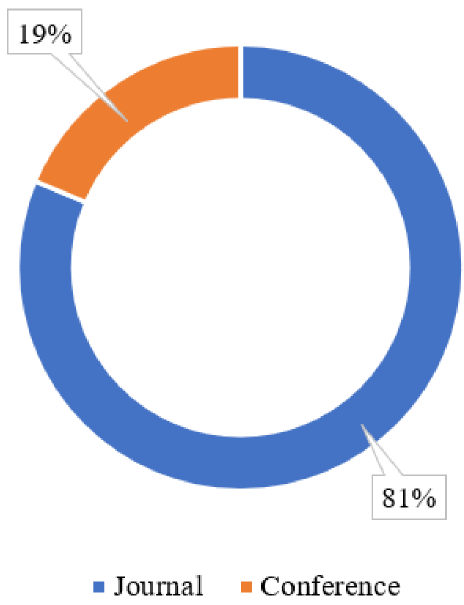

Figure 2.5. Percentage of journal and conference publications

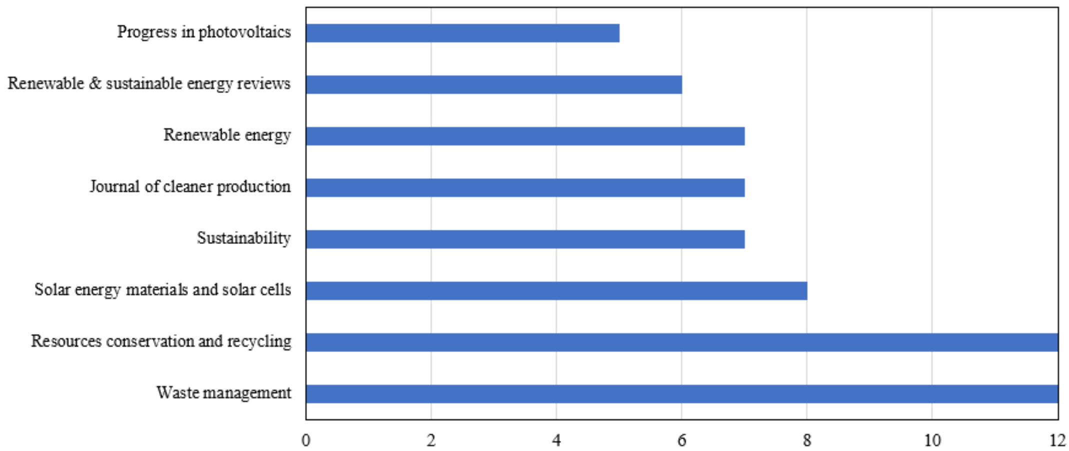

Figure 2.6. Most # of EoL PV publications in a journal

Moving further, out of all the reviewed journal publications (n = 122), the highest number of first authors/primary authors were from European countries. 39.3 percent of the analyzed articles were from EU countries, and the United Kingdom combined, with Italy being the most active, followed by Germany. 27 percent of the publications were from Asia, whereas 20.5 percent were from USA, Canada and Brazil. First authors of only three publications were from Africa whereas 13 out of 122 were from Australia.

The three stand-out countries with the highest number of publications, were USA, Italy and Australia. Table 2.1 summarizes the number of publications produced in each country whereas, Figure 2.7 demonstrates the same data but in the form of a pictorial representation.

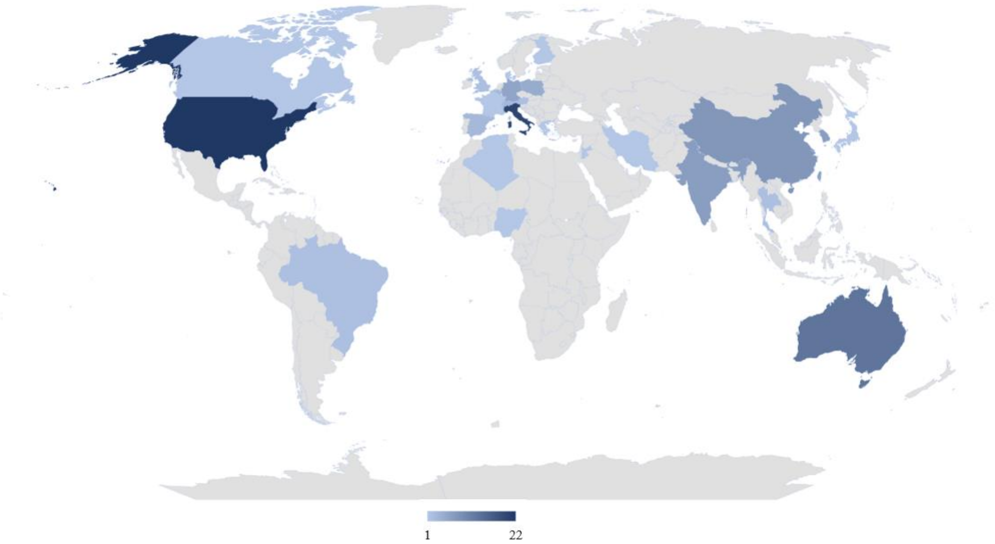

Figure 2.7. Number of publications per country

Furthermore, the methodological trends were examined to observe the approaches adopted in the relevant literature. The research methodologies were categorized as a case study, conceptual, simulation and review. Review papers presented and/or analyzed initial publications on a particular EoL domain. Case studies demonstrated an in-depth examination of a specific problem in a real-world context. Conceptual articles proposed a theoretical framework, whereas, simulation based studies utilized mathematical models and simulations as the basis for decision making.

Case studies have been the most preferred form of research approach as it was employed in 43 articles (35 percent), followed by simulation which was utilized in 32 studies (26 percent). Review articles accounted for about 16 percent of the studies, whereas conceptual articles were 23 percent of the total reviewed journal articles. It is important to note that the number of case study-based articles has gained momentum in recent years, owing to the recent increase in solar PV deployment.

Table 2.1. Region-wise publications on end-of-life solar PV

Region	No. of Articles	Percentage
Europe		*39.3*
Austria	2	
Belgium	3	
Denmark	1	
Finland	1	
France	1	
Germany	6	
Greece	1	
Italy	20	
Poland	5	
Spain	3	
Switzerland	3	
UK	2	
Asia		*27.0*
China	8	
India	7	
Iran	1	
Japan	1	

Jordan	1	
S Korea	7	
Thailand	2	
Taiwan	6	
Americas		*20.5*
USA	22	
Canada	1	
Brazil	2	
Africa		*2.5*
Nigeria	1	
Botswana	1	
Algeria	1	
Australia	13	*10.7*
Total	122	100

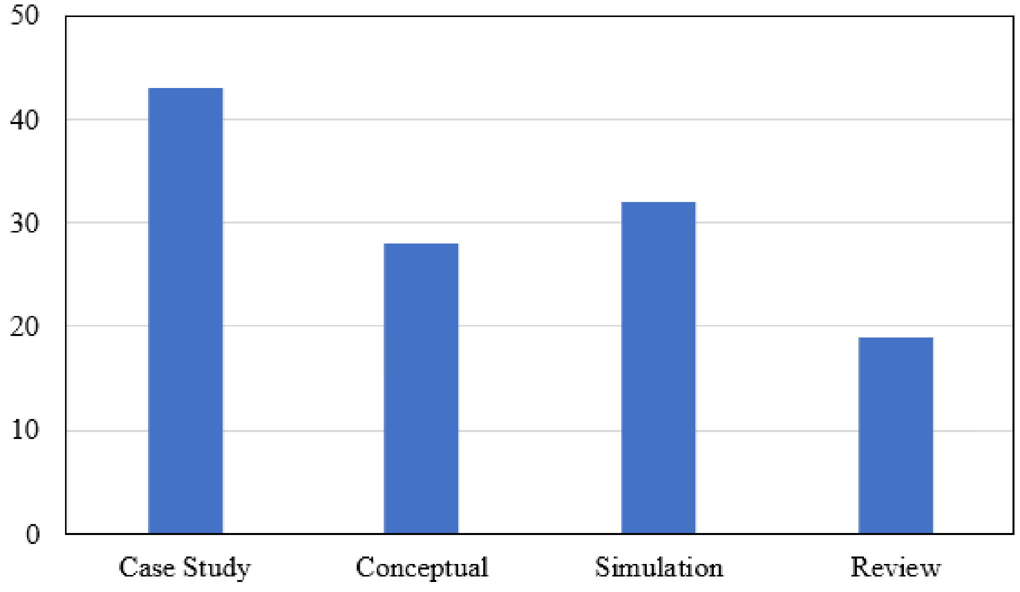

Figure 2.8. Distribution of research methodologies across journals

2.5 Review of some extant studies

Following the systematic literature review, another related and crucial step for developing a holistic conceptual framework is reviewing extant studies in the literature. From the triple bottom line lens and with a viewpoint of gap identification in the pertinent literature, a summary of some relevant end-of-life solar PV studies is presented in Table 2.2.

Table 2.2. Summary of some relevant extant studies

Author(s)	*Forecast*	*Economic*	*Enviro*	*Social*
Cucchiella et al. (2015)	✓	✓		
Latunussa et al. 2016			✓	
Domínguez and Geyer (2017)	✓			
Vellini et al. (2017)			✓	
D'Adamo et al. (2017)		✓		
Corcelli et al. (2018)			✓	
Lunardi et al. (2018)			✓	
Faircloth et al. (2019)	✓	✓	✓	
Mahmoudi et al. (2019)	✓			
Domínguez and Geyer (2019)	✓			
Mahmoudi et al. (2020)	✓	✓	✓	
Klugmann-Radziemska & Kuczynska-Łazewska (2020)			✓	
Markert et al. (2020)		✓		
Herceg et al. (2020)			✓	
Lisperguer et al. (2020)			✓	

Walzberg et al. (2021)				✓
Singh et al. (2021)			✓	
Gautam et al. (2021)	✓			
Ansanelli et al. (2021)			✓	
Mahmoudi et al. (2021)	✓			

2.6 Research gap and scope

Delving deeper into the findings of the systematic literature review combined with an in-depth analysis of the shortlisted studies, the prevailing research themes were identified: environmental impact assessment, forecasting of solar PV waste and economic evaluation, of which environment-centric end-of-life solar PV studies are most recurrent (clearly shown in Table 2.2). Social sustainability, on the other hand, has been the most neglected aspect of end-of-life solar PV due to its obscurity, difficulty in gauging and the fact that social conditions are more dynamic, unlike environmental and economic.

A dearth of integrated end-of-life research, from the lens of triple bottom line, was also recognized. By observing trends in the pertinent literature, it was established that most studies tend to focus on one or two end-of-life aspects, thereby compromising on the totality of the topic. Focusing on all four elements (forecast, economic, environmental and social) provides that comprehensiveness which seemed to be unavailable in the contemporary literature.

With the exception of a few studies, majority of the research focuses on a solitary recycling scenario or atmost a couple of end-of-life options by disregarding the fact that including various disposal options would provide more leverage in comparing the economic, environmental and social implications. Incorporating multiple end-of-life scenarios will not enrich the study itself but also offer a more holistic and broader perspective that could potentially facilitate decision-makers in devising circular and sustainable policies.

Taking a step further, the implementation of end-of-life frameworks in a region/country as case study was observed to be relatively limited. With the rapidly increasing end-of-life PV waste, it is indispensable that sustainability assessment frameworks devised by academicians and researchers are implemented to underpin the research itself and provide a better understanding to the policymakers by outlining real-life sustainability implications. This can further be augmented via a multi-criteria decision analysis, where different end-of-life options can be ranked for their environmental, economic and social sustainability performance.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the adopted steps for responding to research questions (RQ1 - RQ4) by emphasizing the methods in the literature for attaining the research objectives. These methods broadly include: conducting a holistic literature review, evidencing the identified research gaps to develop a conceptual framework and implementing the framework in a specific region as a case study. The details of the employed research strategy throughout the research are outlined and justified in this chapter.

3.2 Research methods and overview

To attain the thesis objectives through methodological rigor, the following steps essential for comprehensive research, as outlined by (Saunders et al. 2015), have been undertaken:

1) Literature review: This section characterizes the initial phase of the research, where a detailed review of the pertaining literature was conducted to establish the research topic and articulate the research problem. Within this section, the research questions were also formulated, and the research gaps were identified based on which the conceptual framework was developed.
2) Conceptual framework: Conducted as the second step of the research, this section outlines a framework, from the lens of a triple bottom line, that can be applied to a specific region to ascertain the sustainable management of various end-of-life PV disposal options.

3) Implementing the framework and further elucidation: The conceptual framework established in the previous section is implemented in a specific region to demonstrate its efficacy to policymakers and industry practitioners. Moving further, when implemented in a particular region, the outcomes are elaborated to provide a detailed understanding of the findings.

Based on these techniques, the thesis entails three essential phases to achieve the research targets, as tabulated in Table 3.1.

Table 3.1. Phase, research question and research objectives

Phase	*Research question*	*Research objective*
Literature review	RQ 1: Why is sustainable management of end-of-life PV a potential research avenue?	Conduct a systematic literature review of end-of-life solar PV management and identify the key research gaps and opportunities.
Conceptual framework	RQ 2a: How can sustainable management decisions regarding end-of-life solar PVs be made holistically? RQ 2b: What are the steps required to be taken towards sustainable management of end-of-life solar PVs?	Develop a conceptual framework including waste forecasting, triple bottom line (environmental, economic and social) and multi-criteria decision analysis (collecting expert responses).
Implementation of framework	RQ 3: How can such a sustainable management approach framework be implemented or operationalized on a specific region?	Implementing the conceptual framework on a specific region to validate the practicality of the framework.
Discussion & further elucidation	RQ 4: What are the key drivers, barriers and enablers to sustainable end-of-life solar PV management	Highlight the barriers, promote the drivers and effectively outline the enablers

A detailed review of the literature was conducted and presented in chapter 2, where a significant end-of-life solar PV management problem was established, research questions were contrived, and vital themes and opportunities in the extant literature were analysed. Stemming from these research gaps and opportunities, a detailed synergy of end-of-life PV and sustainable management was derived in line with research question 1.

Two main reasoning techniques were discerned for answering the research questions: inductive and deductive. The deductive approach characterises a method where a conceptual framework is first developed, and the data is collected subsequently, whereas an inductive approach marks data collection before deriving a conceptual framework (Creswell & Clark 2011; Saunders et al. 2015).

The advantage of employing a deductive approach in research is that the conceptual framework can be devised so that the research objectives and conceptual standpoints can be catered (Saunders et al. 2015). Furthermore, the deductive approach steers the research by fulfilling the research objectives through a carefully developed framework. The connections between the extant literature and research can conveniently be established, and the data collection phase (through expert responses) can be conducted more structured, reducing subjectivity and reliance on interpretation (Saunders et al. 2015).

On the contrary, developing and synergising theories in advance can potentially curtail the scope of research that might be crucial to the phenomenon being explored and investigated (Bryman 2003). Employing a deductive research outlook was justifiable because of its apparent advantages, such as its organised and structured nature and alignment with the research aims.

The literature review was succeeded by a conceptual framework, in line with the two components of research question 2. The importance of this section in research has been emphasised in various studies (Suddaby 2014; Imenda 2014; Adom et al. 2018). According to (Imenda 2014) conceptual frameworks "bring together a number of related concepts towards broader understanding of phenomenon or achievement of research objectives”. A conceptual framework is developed to underpin the research and its objectives. Adom et al. (2018) explained conceptual frameworks as “consisting of concepts interconnected to explain the relationships between them and how the researcher asserts to answer the research problem defined, aimed at advancing the 84 development of a theory in a way that would be useful to practitioners in the field”.

Stemming from the significance of a conceptual framework, a synergy between end-of-life PV options and sustainability evaluation was formulated from the lens of a triple bottom line. The research gaps identified in the literature review were scrutinized and framed under a pragmatic and coherent framework. The linkages between the PV waste flow, environmental impact assessment, economic and social evaluation were developed. A multi-faceted questionnaire was devised that was in turn utilised for collecting expert responses during the implementation stage for calculating the weights of criteria and sub-criteria

The implementation of the conceptual framework was then carried out as a case study. As mentioned earlier, expert responses were collected to carry out a MCDA and obtain sustainability scores for each disposal scenario. Further interpretation of the results alongside the drivers, enablers and barriers of sustainable end-of-life PV management were then elucidated in the discussion section.

The interconnectivity between the research questions through the deductive approach and critical sections of the research are illustrated in Figure 3.1.

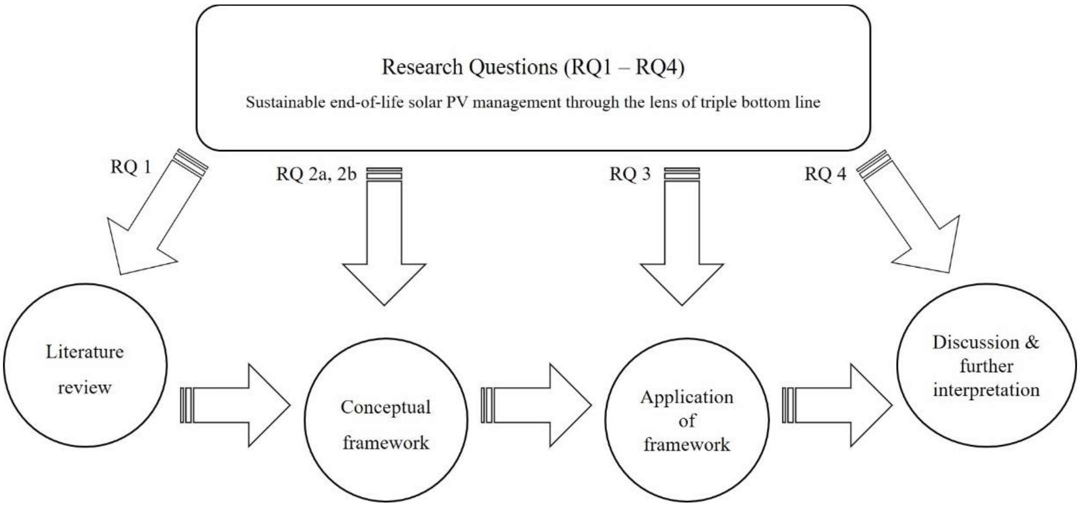

Figure 3.1. Research map

CHAPTER 4

CONCEPTUAL FRAMEWORK

4.1 Introduction

This chapter outlines this thesis's conceptual framework, which is in accordance with the research questions presented in the introduction. An overview of the conceptual framework is outlined in Section 4.2.

Based on the outcomes of the systematic literature review and evidencing the identified gaps further, this chapter outlines a framework that integrates the waste projection of end-of-life solar PV (Section 4.3), environmental impacts through the life cycle assessment (Section 4.4), economic evaluation (Section 4.5) and social aspects (Section 4.6) pertaining to the four disposal scenarios.

Furthermore, a multi-criteria decision analysis, comprising a multi-attribute value theory, is conducted (Section 4.7) to ascertain the individual and cumulative sustainability scores for each waste disposal scenario.

4.2 Overview of conceptual framework

The conceptual framework aims to provide a roadmap for gauging the extent of sustainability of end-of-life options for solar PV. For this reason, a holistic step-by-step approach has been devised to evaluate the overall sustainability of a disposal scenario from the lens of a triple bottom line. The overview of the conceptual framework is illustrated in Figure 4.1.

Projecting PV waste is vital to assess end-of-life environmental, economic and social impacts. To accurately estimate the PV waste flow in future, a dedicated sub-section (Section 4.3) has been included in the conceptual framework.

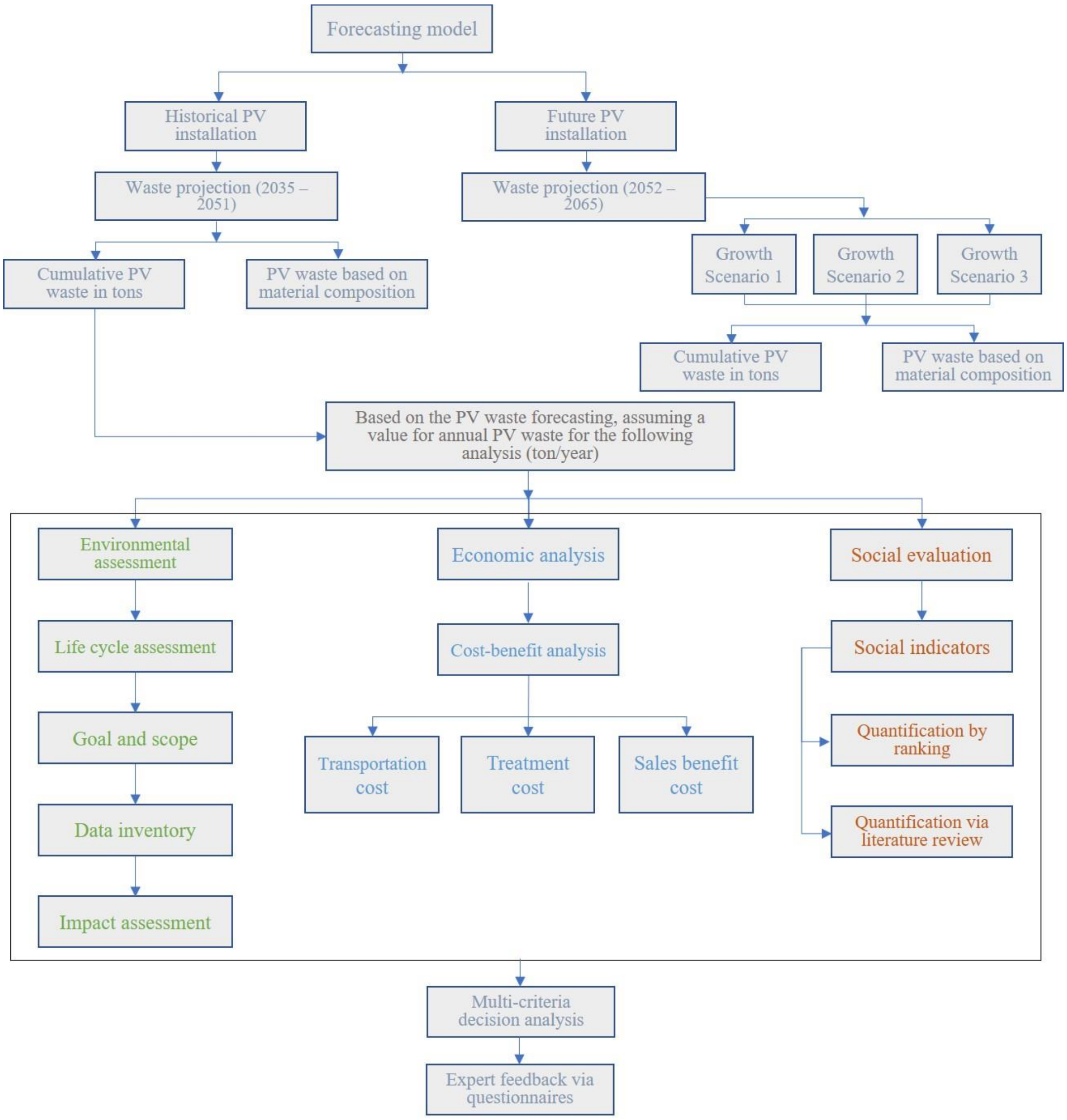

Figure 4.1. Overview of conceptual framework

Forecasting of waste streams has been conducted through many variations of the input-output forecasting model, such as the time step approach, Carnegie Mellon technique and market supply method (Araújo et al. 2012; Paiano 2015). Due to the assumption of a constant life span, these models disregarded the possibility of early failure (Peeters et al. 2017). Melo et al. (1999) suggested utilizing a Weibull function to forecast the waste flow because of its convenience in fitting onto the actual life span data. The Weibull function, as a consequence, has abundantly been employed not only in forecasting emerging waste streams (Paiano 2015; Santos & Alonso-

García 2018; Mahmoudi, Huda, & Behnia 2019; Gautam et al. 2021) but also for estimating the solar energy yield (Ghitany & El-Nashar 2005; Kam et al. 2021; Garbai & Kovacs 2021).

The disposal scenarios were then evaluated from environmental, economic and social sustainability perspectives. Before emphasizing and outlining the triple bottom line sustainability evaluation, the four end-of-life PV options were established, which are also illustrated in Figure 4.2. Scenario 1 represents a direct landfill where the overall recovery is zero. Scenarios 2 and 3 characterize the downcycling approach. In Scenario 2, only the aluminium frame and copper cables are recovered, and the remaining PV panel waste is shredded before being disposed to the landfill. In Scenario 3, glass cullets and some other materials are recovered, signifying that this scenario is more sophisticated than the previous. Scenario 4 demonstrates an upcycling approach, where the entire PV panel waste is recycled.

Considering the environmental aspect, various indicators and tools have been developed for evaluating and benchmarking the environmental implications of different systems. These include life cycle assessment (LCA), environmental risk assessment, ecological footprint (EF), environmental impact assessment (EIA) and others (Ness et al. 2007; Finnveden et al. 2009). LCA was chosen over the other environmental assessment tools because of its unique focus on a product from a life cycle perspective (Finnveden et al. 2009). Moreover, the results from the LCA provide a decision worthy information related to product development and product system improvement at the consumer level (Ness et al. 2007).

LCA has conventionally been a choice for the environmental evaluation of products. EIA, on the other hand, is preferred for the assessment of projects (Finnveden & Moberg 2005). Therefore, the objective of the research is crucial to deciding which environmental indicator or tool would be a natural choice. Life cycle assessment has been popularly utilized for a multitude of products across various industries, such as agriculture (Caffrey & Veal 2013; Kulak et al. 2013; Martínez-Blanco et al. 2013; van der Werf et al. 2020), automotive (Hawkins et al. 2013; Pero et al. 2018;

Tolomeo et al. 2020), construction (Buyle et al. 2013; Abd Rashid & Yusoff 2015; Balaguera et al. 2018), primary metals (Nuss & Eckelman 2014), energy and waste (Evangelisti et al. 2014; Gong et al. 2015; Mayer et al. 2019).

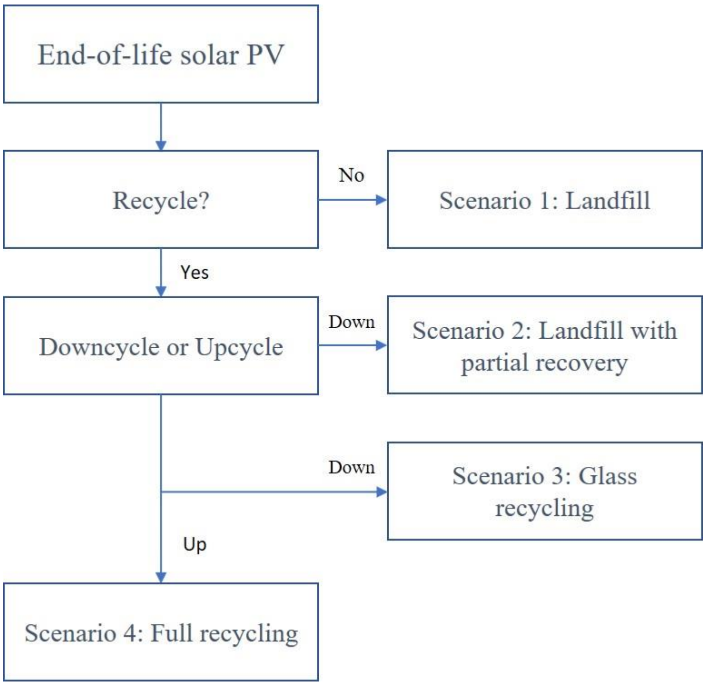

Figure 4.2. End-of-life PV scenarios

The next phase involves economic evaluation, which has extensively been carried out in the literature through a cost-benefit approach (Ness et al. 2007; Cucchiella et al. 2015; Zhou et al. 2015; D'Adamo et al. 2017; Zhan et al. 2019). The cost-benefit analysis, an applied welfare economics tool, is a valuation method to estimate and forecast if an investment can achieve or not profitability (Ness et al. 2007; Tudisca et al. 2013). Following the pathway of other relevant studies in the literature, this research utilizes a cost-benefit model to present the economic outcomes.

Social sustainability has been gaining popularity in the literature for its intrinsic relevance to sustainable development (Bijl 2010; Whitton et al. 2015), with previous research usually limiting itself to economic and environmental aspects (Colantonio 2009; Eizenberg & Jabareen 2017; Bonilla-Alicea & Fu 2022). However, gauging social sustainability is difficult (Assefa & Frostell 2007). Studies focusing on social sustainability have utilized social life cycle assessment (Kühnen & Hahn 2017; Bonilla-Alicea & Fu 2022). However, due to the challenge of collecting valid data (Kruse et al. 2009) and the results being fairly complex for decision makers (Traverso et al. 2012), S-LCA has not been a prevailing choice. Moreover, the social conditions are dynamic, which means that social data changes quicker than environmental data, further restricting the implementation of a social life cycle assessment (Wu et al. 2014; Hossain et al. 2018).

On the contrary, the indicator-based approach, where the indicator data is either collected through a literature-based deduction or via multi-criteria decision analysis such as analytic hierarchy process (AHP), pairwise comparison and multi-attribute value theory (MAVT), is a more prevalent option. The reason is its simplicity and robustness (Assefa & Frostell 2007; Wang et al. 2009; Milutinović et al. 2014; Olakitan Atanda 2019; Deshpande et al. 2020).

Incorporating this approach in the research, the relevant social indicators were identified, which were quantified through a combination of the author's deduction and information from the literature. To determine the overall sustainability score for each end-of-life scenario, a popular multi-criteria decision analysis method: multi-attribute value theory (Wang et al. 2009; Santoyo-Castelazo & Azapagic 2014), was adopted. The expert responses were analysed through the multi-attribute value theory to calculate the criteria and sub-criteria weights.

4.3 PV panel waste projection

The projection of PV waste flow can be based on two scenarios: current PV installations and future PV installations. For the first scenario, the year-by-year data of PV installations is readily accessible for major countries in the context of solar photovoltaics. Therefore, utilizing this data for estimating the PV waste flow is convenient and more reliable. On the contrary, forecasting future PV installations can be arduous because of various factors such as economic growth, government policies, cost etc., that could potentially impact the future solar PV penetration rate. Mahmoudi et al. (2019) proposed an approach where multiple solar PV growth scenarios are considered to forecast the PV waste flow. This technique is case-sensitive as the solar PV growth rate can vary significantly from country to country. However, by employing this approach, various PV waste flow scenarios can be estimated, which provides an improved understanding of the amount of end-of-life PV in a given period.

The waste forecasting model accounts for three waste projection scenarios: fixed loss, early loss and regular loss. In the fixed loss scenario, the central assumption is that the PV panel reaches its end-of-life after a fixed life span, after which it is to be replaced. The useful life span of a PV panel for fixed loss is considered 30 years.

The early and regular loss scenarios are modelled via the Weibull reliability function in various studies (Santos & Alonso-García 2018; Gautam et al. 2021), as demonstrated in *equation (1)*, where 'P(t)' is the distribution function of Weibull, 't' is the PV panel life (years), 'τ' is the average panel lifetime (years) and 'β' is the shape factor.

$$P(t) = 1 - e^{-\left(\frac{t}{\tau}\right)^{\beta}} \tag{1}$$

Shape factor refers to the evolution of the PV panel failure with time. For the regular and early loss scenario, the value for the shape factor is 5.3759 and 2.4928, respectively (Santos & Alonso-García 2018; Mahmoudi, Huda, & Behnia 2019; Gautam et al. 2021). Moreover, both regular and early loss scenarios assume a 30-year average lifespan and a 99.99% probability of the panel's life loss after 40 years (Santos & Alonso-García 2018).

Degradation of panels is also a crucial factor that can be accounted in the early loss scenario (Santos & Alonso-García 2018; Gautam et al. 2021). The rate of degradation can vary across regions due to various environmental conditions like extreme temperature, high levels of humidity, wind speed etc., The degradation rates from different regions/countries have been summarized in Table 4.1 (Kim et al. 2021). The degradation rate for an early loss scenario can be computed using *equations (2)* and *(3)*, where 'u_e' is the rate of power loss for early scenario and 'd' is the degradation rate (Gautam et al. 2021).

$$u_e = x_i\ (1 - d)^t \tag{2}$$

$$u_e = P\ (t) \tag{3}$$

The PV panel waste in tons for a given period can be determined by utilizing *equation (4)*, 'u_x' is PV installed in MW/year, 'w' is weight in ton/MW, 'x' is the year and 'y' is waste generation year (Paiano 2015).

$$w_y = \sum_{x=1}^{y} u_x w \tag{4}$$

The specification, including area, power, weight and efficiency from various datasets, were extracted and summarized in Table 4.2 (Paiano 2015; Mahmoudi, Huda, & Behnia 2019). To obtain the average weight, the panel weight is divided by power and is also included in Table 4.2. The slight deviation in value of the average weight across different datasets is logical due to the difference in weight and power of a solar panel.

Furthermore, for early and regular loss schemes, the weight of installed PV panels in any given year can be multiplied by the Weibull function for calculating the cumulative PV panel waste.

4.3.1 PV waste metal inventory and recovery

The total inventory and quantity of metals that can potentially be recovered from the PV panel waste can be ascertained. The waste composition of the decommissioned panels includes glass, aluminium, EVA, silicon, copper, tin, lead, steel, magnesium, titanium and nickel. The amount of PV waste for each material can be determined by the total waste annually (in tons) by the material composition. Moving further, the amount of recovered waste can be estimated by multiplying the recovery rate and amount of waste (by material).

Table 4.1. Degradation rates for different regions

Region		*Reason of Degradation*	*Rate of Deg. (%/yr)*
Europe	Spain	Speed of wind	− 0.8 to −1.1
	Italy	PV cell shading	−0.8 to −1.1
	Cyprus	Cell temperature and solar irradiance	−0.8 to −1.1
	Poland	Increased air temperature	>−0.9
	Scotland	Extreme low temp and humidity	−1.05 to −1.16
Asia	India	High cell temp and humidity	−1.4
	Thailand	Humidity and moisture	−1.5 to −4.9
	Korea	Corrosion and discoloration	−1.3
	Japan	Environmental factors (ambient)	−1.15
	Singapore	Ambient temperature	−2.0
Australia	Australia	Extreme high temperature and moisture	−1.35 to −1.46

Table 4.2. PV panel specifications for different datasets

Dataset	*Area (m^2)*	*Power (Wp)*	*Weight (kg)*	*Efficiency (%)*	*Average weight (kg/Wp)*
Ecoinvent	1.46	224	23	15.3	0.103
First Sunergy	1.59	230	23	14.4	0.100
Perseidsolar	1.69	225	25	13.3	0.111
BIO Intelligence Service	-	-	-	-	0.102

4.4 Life cycle assessment (LCA)

LCA is conducted based on the International Organization for Standardization (ISO) 14040 series. The LCA comprises of four stages, also demonstrated in Figure 4.3: 1) goal and scope definition (ISO 14040), 2) life cycle inventory analysis (ISO 14041), 3) life cycle impact assessment (ISO 14042), and 4) interpretation of the findings (ISO 14043). Stage 4, the interpretation of the LCA findings, is discussed later in Sections 5 and 6.

4.4.1 Goal and scope

The objective of a life cycle assessment is to identify the environmental impacts in the context of this research pertaining to the various end-of-life solar PV scenarios. The four scenarios considered in the scope of this study include disposal to landfill (Scenario 1), disposal to the landfill with some material recovery (Scenario 2), glass recycling (Scenario 3) and full recycling (Scenario 4).

To solely focus on the end-of-life aspect, the scope of this life cycle assessment is 'gate-to-gate' within a system boundary. Therefore, the collection/transportation and landfill/recycling phase are included. Other components, such as inverters, transformers, etc., are disregarded to keep the focus of the LCA purely on end-of-life solar PV panels.

4.4.2 Life cycle inventory

This section is further divided into two sections: 1) description of the four disposal processes and 2) inventory data that will be utilized for the life cycle assessment.

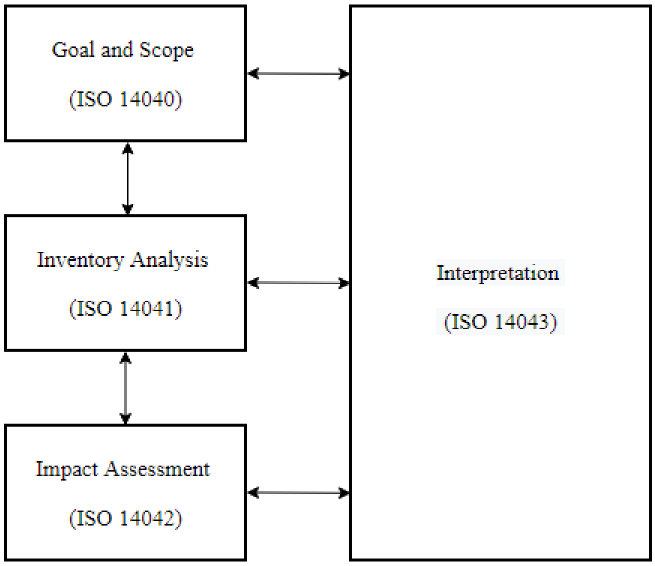

Figure 4.3. Relationship between the 4 LCA stages

4.4.2.1 Description of the disposal processes

Disposal to landfill is separated into two distinct scenarios: scenario 1 signifies direct disposal to landfill, whereas scenario 2 involves manual disassembly and shredding before the waste is dumped into the landfill. The first stage of disposal to landfill consists of the transportation of end-of-life PV to the nearest landfill site. In scenario 1, the PV panel is disposed into a landfill as a single piece to reduce the potential of leaching and penetration of toxic metals into the soil. Having said that, there are breakages during the transportation phase, and therefore, at the time of disposal, some PV panels are already broken (Daljit Singh et al. 2021).

In scenario 2, the PV waste is unloaded, and the aluminium frame is manually disassembled. Since the manual disassembly is quite efficient, about 95 percent of the aluminium is recovered. The aluminium and cable connector is sent further for recycling, whereas the remaining waste PV panel are crushed into smaller fragments via shredders. Since the residual fraction is not suitable for recycling after hammering and shredding, the PV sandwich is disposed into the landfill (Latunussa et al. 2016). The process diagram and system boundary for scenario 2, including the inputs and outputs, are illustrated in Figure 4.4.

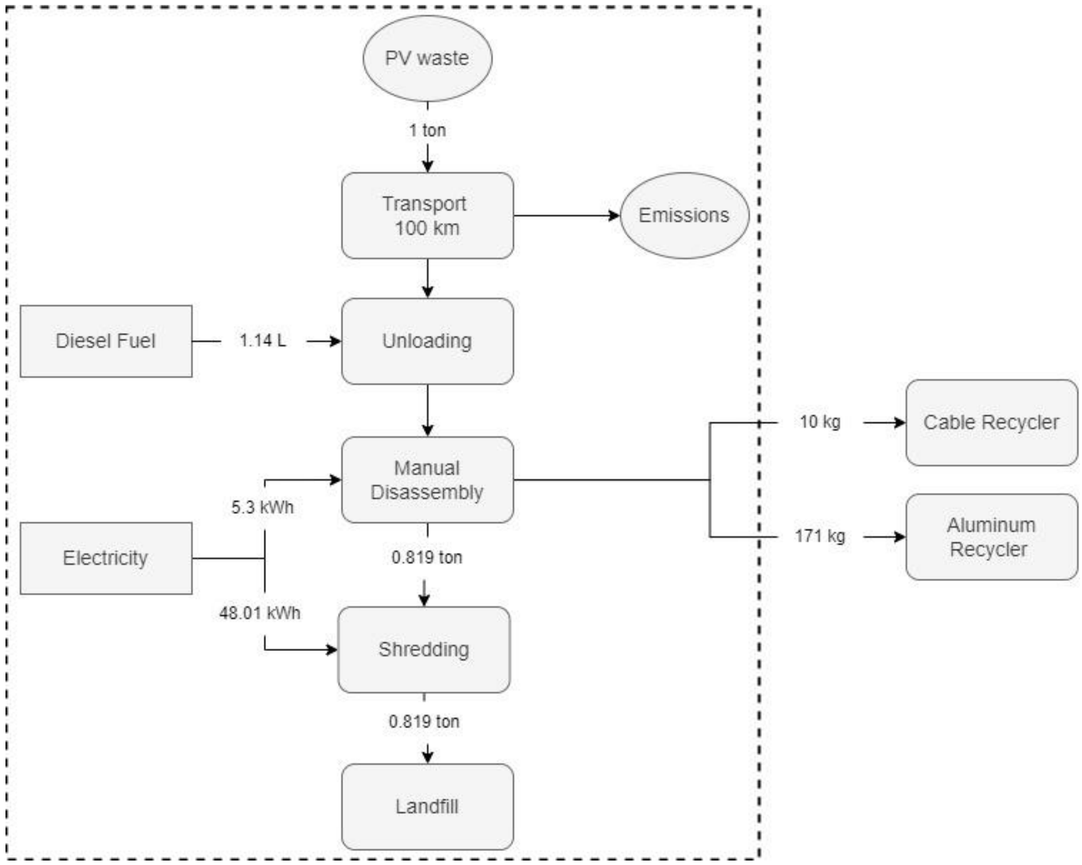

Figure 4.4. System boundary for scenario 2

In scenario 3, laminated glass recycling at the Maltha glass facility in Belgium is considered. The PV waste is first transported to a designated recycling facility and where it is unloaded. The manual removal of the aluminium frame, junction box and copper cables then takes place. The remainder of the PV module is then transported via a wheel loader to the glass recycling line, where the recycling process is initiated by crushing and shredding the modules. Subsequently, the ferrous metals are separated using a magnetic separator and extracted.

The remaining waste goes through fine crushing and is screened into glass, foils and fines. The non-ferrous metals are then removed through eddy current devices, after which the impurities such as ceramic and porcelain are removed through sieving. The main outputs (recovered materials) through the laminated glass recycling are glass, copper and aluminium. The system diagram illustrating this recycling process is shown in Figure 4.5.

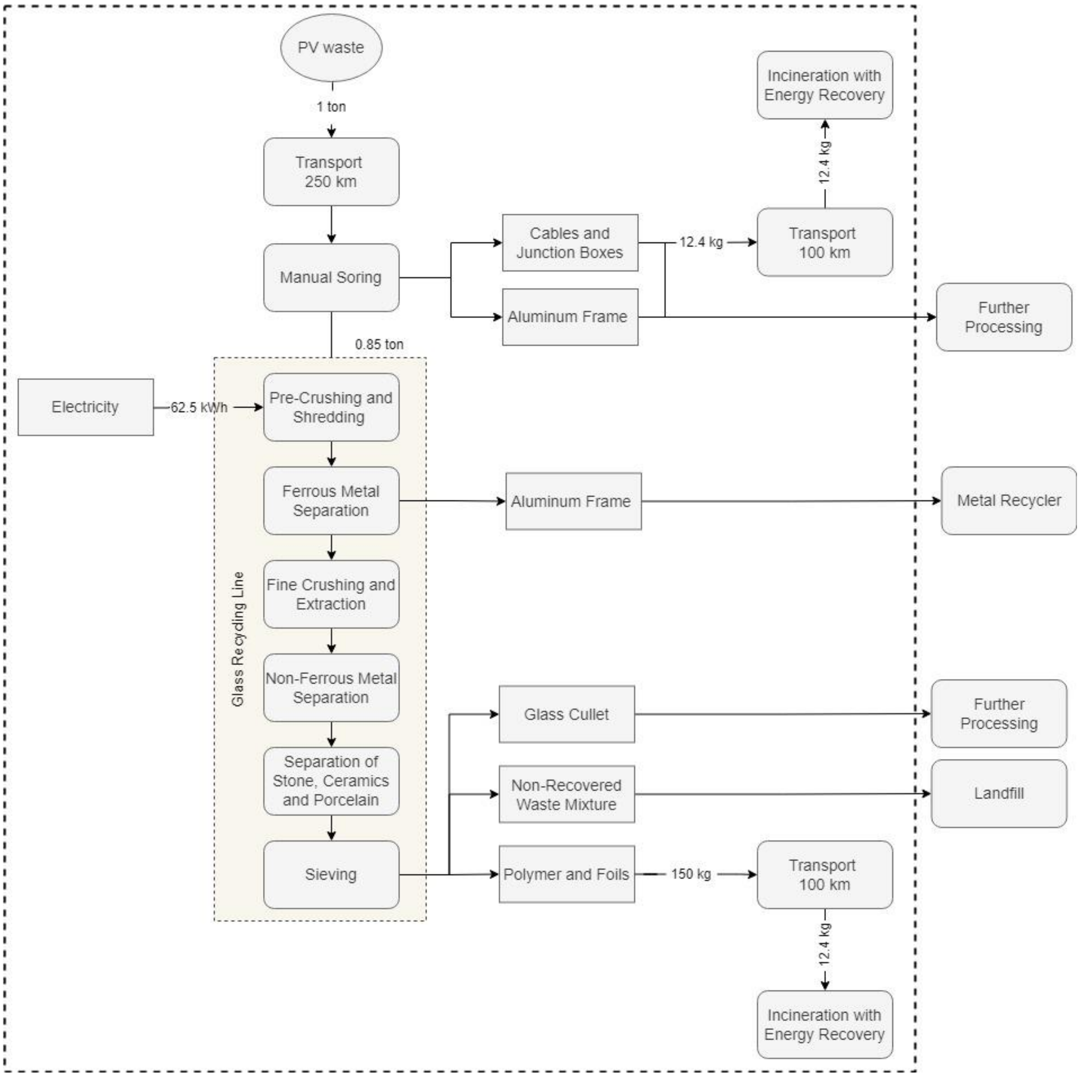

Figure 4.5. System boundary for scenario 3

Scenario 4 represents the full recycling scenario, and the pertinent inventory and process data were obtained from FRELP: a pilot project (Latunussa et al. 2016). Post arrival of PV waste in the recycling facility, the end-of-life PV are unloaded using a forklift and placed on a conveyor belt. Towards the end of the conveyor belt, a

Cartesian robot detaches the junction box, cables and aluminium frame. The waste modules are then brought for glass separation, where the glass layer is delaminated from the remaining module layers via infrared radiation. The yield of this process is a PV sandwich and PV glass. Following, the separated glass is sent for glass refinement for maximum recovery, after which the impurities are disposed of in a landfill. The remaining PV sandwich goes through a cutting process, which is transported to an incineration plant for further treatment. The output residual bottom ash is returned to the recycling plant to recover the necessary cell materials. The ash is sieved, and the residues are transferred for acid leaching.

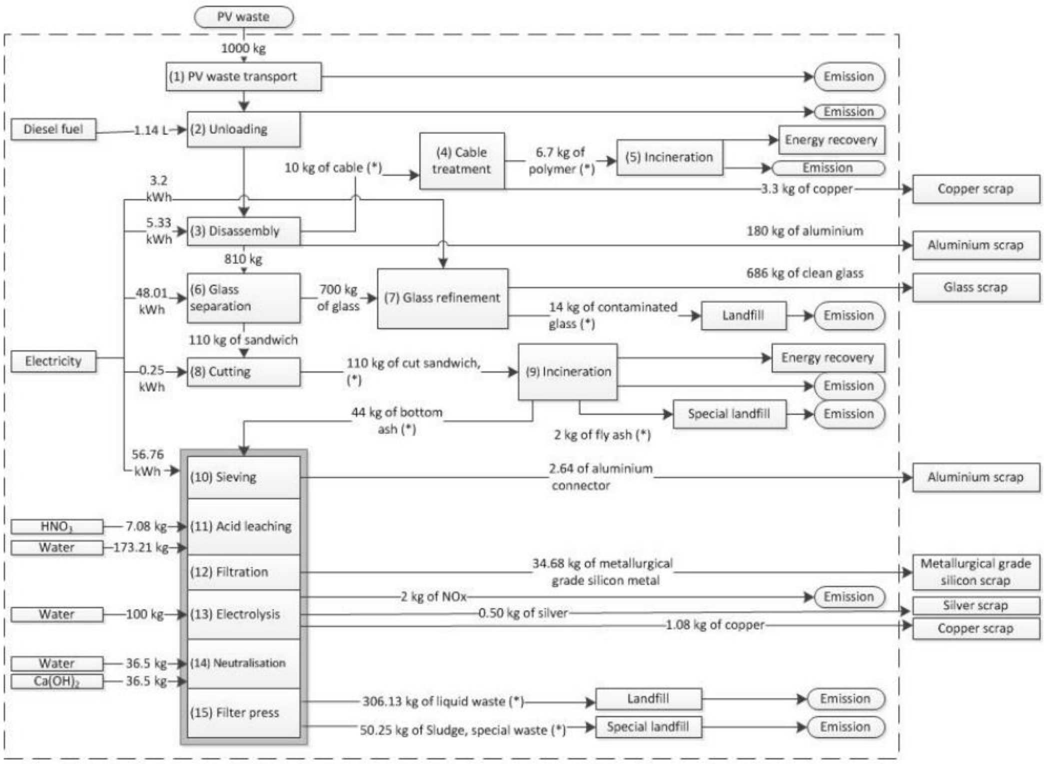

Figure 4.6. System boundary for scenario 4

Acid leaching is carried out to isolate silicon from the remaining metals in the bottom ash. This is done by mixing ash in a mixture of nitric acid and water solution due to which the metals are dissolved, leaving behind silicone as residue. The dissolved metals and silicone residue is passed through a filtration process to remove silicone.

The remaining filtered acid solution is treated by electrolysis to recover copper, aluminium and silver. The depositions of electrolysis that exist in the solution are neutralized by calcium hydroxide, and a filter press finally filters the output. The system diagram illustrating this recycling process is demonstrated in Figure 4.6 (Latunussa et al. 2016).

4.4.3 Life cycle impact assessment

The third phase of the life cycle assessment involves the impact evaluation, which was carried out using the OpenLCA 1.10 software by Green Delta. Impact assessment methodologies such as CML 2001, ReCiPe, Impact 2002+, IPCC 2013 etc., have been employed in the literature. However, there is no scientific evidence to prove that a particular impact evaluation methodology is superior to another; instead, the selection is based on the objective and context of the LCA (Campos-Guzmán et al. 2019).

The LCA in this thesis includes the ReCiPe impact assessment, where the midpoint indicators emphasize particular environmental concerns. The midpoint impact categories include: agricultural land occupation (m2a), natural land transformation (m2), urban land occupation (m2a), climate change (kg CO2-Eq), fossil depletion (kg oil-Eq), ozone depletion (kg CFC-11-Eq), freshwater ecotoxicity (kg 1,4 DCB-Eq), freshwater eutrophication (kg P-Eq), marine ecotoxicity (kg 1,4 DCB-Eq), marine eutrophication (kg N-Eq), human toxicity (kg 1,4 DCB-Eq), ionizing radiation (kg U235-Eq), metal depletion (kg Fe-Eq), water depletion (m3), particulate matter formation (kg PM10-Eq), terrestrial acidification (kg SO2-Eq), terrestrial ecotoxicity (kg 1,4- DCB-Eq) and photochemical oxidant formation (kg NMVOC). The reason for disregarding the endpoint indicators was the oversimplification in the interpretation of the impact assessment results that increases uncertainty with each aggregation step.

In the ReCiPe method, three different uncertainty perspectives can be employed: egalitarian (E), individualist (I) and hierarchist (H). The egalitarian perspective represents the longest time frame (1000 years) and employs a precautionary approach, whereas the hierarchist considers a moderate time frame (100 years). Individualist accounts for a short-term (20 years) and an optimistic approach (Daljit Singh et al. 2021). In this thesis, the hierarchist perspective was accounted as it was seen as a more reasonable time frame.

4.5 Economic assessment

As mentioned in the overview section, the economic assessment is conducted through a cost-benefit model in which a holistic mathematical framework is adapted (Cucchiella et al. 2015; Faircloth et al. 2019; Liu et al. 2020; Mahmoudi et al. 2020) estimates the costs incurred and sales benefit if any.

The sales benefit is generated through the revenue from recycled materials (without secondary processing) and heat/electricity generation by incineration. The financial value of the recovered material depends on the market price and recovery rate. On the other hand, the incurred costs include collection and transportation costs, processing costs (material and electricity costs), staff wages, waste disposal costs, depreciation costs and financing costs.

The factors impacting the transportation cost include the quantity of waste (Q), and total distance (D) travelled (both to the collection point and recycling facility). The transportation cost also contains the air emission cost (ET) in addition to the actual transportation cost (F). *Equation* (5) can be utilized to compute the total cost of collection and transportation.

The depreciation cost of fixed assets, determined by *equation* (6), is carried out through a prevailingly utilized straight-line depreciation method, where ‘w’ is a salvage value and ‘Y’ is the mean depreciable life.

The financing cost is computed using *equation* (7), where 'r' is the annual interest rate and 'β' is the capital equity ratio. It is assumed that the depreciation and financing cost is only associated with scenario 4, which would require the maximum investment cost. The assumption of discounting the depreciation and financing cost is confirmed in the literature (Deng et al. 2019). The equipment maintenance cost is a percentage of the depreciation cost. *Equation* (8) is utilized to obtain the total labor cost, where 'S' represents salary and 'N' signifies the number of workers.

Raw material cost was determined by *equation* (9), where 'Q' is the quantity of PV waste and 'Pr' is the raw material price. The disposal cost of a landfill can be determined through *equation* (10), where 'Q' is the disposal quantity, and 'Cd' is the landfill cost per tonne disposal.

$$TC = Q * D * (F + ET) \quad (5)$$

$$DPC = I * \frac{(1 - w)}{Y} * 100 \quad (6)$$

$$FC = I * (1 - \beta) * r \quad (7)$$

$$LC = S * N \quad (8)$$

$$RMC = Q * Pr \quad (9)$$

$$DC = Q * Cd \quad (10)$$

The benefits or the cash inflow can be calculated through *equation* (11), where not only the monetary benefit associated with the recovered materials is accounted for but also the cost of energy recovery through incineration and environmental benefits through recycling are considered.

$$B = Q * \sum_m (Rm * Pm) + \text{Cer} \quad (11)$$

4.6 Social assessment

Indicator identification is pivotal for conducting a comprehensive social impact assessment. Having said that, no universal social indicators or methodology can be incorporated directly (Bonilla-Alicea & Fu 2022). As a result, social indicators pertinent to the scope of this research were identified and extracted through expansive literature research (Kühnen & Hahn 2017; Bonilla-Alicea & Fu 2022; Ganesan & Valderrama 2022). The social indicators employed in this research include contribution of technology to economic progress, energy security, health & safety of workers, local job creation, consumer awareness & public participation and eco-industrial partnership.

The indicators above can be utilized in future studies focusing on the social evaluation of end-of-life solar PV and other comparable studies such as sustainability of electricity generation technologies, waste management and recycling. To ameliorate the objectivity while interpreting the results, additional information regarding each social indicator is tabulated in Table 4.3. In Table 4.3, alongside the indicator name, indicator type, stakeholder group and impact category are also provided to ensure transparency when presenting the results. The reason for including the impact category and stakeholder group is to provide further outlook on the broader perspective and inform about the relevant stakeholder for each social indicator.

Five of the six social indicators have been included under the semi-quantitative type, whereas only one indicator is considered quantitative. The semi-quantitative indicators are quantified using a ranking system (4-point Likert scale), where a rank of ‘1’ represents high performance, ‘0.5’ signifies medium performance, whereas ‘0.25’ and ‘0’ characterize low performance and not relevant, respectively (Deshpande et al. 2020; Bonilla-Alicea & Fu 2022). The rank allocation to the indicators, as done previously by studies in the literature, can be assigned based on the overall understanding of the author acquired via the course of their literature review and expertise and via discussion with stakeholders and experts (Milutinović et al. 2014; Deshpande et al. 2020; Bonilla-Alicea & Fu 2022; Ganesan & Valderrama 2022).

Table 4.3. Selected social indicators

Name	*Type*	*Impact category*	*Stakeholder group*
Contribution of tech to economic progress	Semi-quantitative	Economic development	Society
Energy security	Semi-quantitative	Societal impacts	Society
Health & safety of workers	Semi-quantitative	Health & safety	Workers
Local job creation	Quantitative	Employment	Local community
Consumer awareness & public participation	Semi-quantitative	Public commitment & participation	Consumer
Eco-industrial partnership	Semi-quantitative	Industry, innovation & infrastructure	Value-chain actors

4.7 Multi-criteria decision analysis

The literature was expansively explored to select the appropriate multi-criteria decision analysis method for ascertaining the most sustainable end-of-life PV disposal option. Among the various MCDA approaches, MAVT was selected for its simplicity, robustness and transparency in prompting expert responses and stakeholder choices (Osterwalder et al. 2014). MAVT has been characteristically utilized for ranking various alternatives through the opinion of pertinent stakeholders to determine the most appropriate solution (Stefanopoulos et al. 2014).

The criteria included for assessment were carefully devised to minimize the uncertainty alongside gauging the performance of the end-of-life PV scenario against a defined goal. The indicators (economic, social and environmental) were selected based on a prudent literature survey. The five indicators shortlisted for evaluating environmental performance include climate change, ozone depletion, fossil depletion, terrestrial acidification and human toxicity. Five indicators finalized for economic performance comprise transportation cost, processing cost, labour cost, disposal cost and revenue generation through material recovery. Lastly, six indicators for social evaluation include the contribution of technology to economic progress, energy security, health and safety of workers, local job creation, consumer awareness and public participation and eco-industrial partnership. The reason for choosing these indicators was their relevance to this research, which can be validated from similar studies in the literature (Deshpande et al. 2020; Ganesan & Valderrama 2022).

Incorporating expert input and cognizance while choosing and ranking assessment criteria is widespread in multi-criteria decision analysis studies (Tsai et al. 2018). Consequently, a simple yet comprehensive questionnaire was framed and circulated among the experts through email and a social media platform (LinkedIn). The questions included in the questionnaire are presented in the Appendix section. The responses are coalesced to depict the distribution of priorities by the experts (Collier et al. 2014). *Equation* (12) was employed to convert the points assigned to criteria and sub-criteria into weights where 'W_i' is the criteria weight, 'S_i' is score assigned to the criteria, and 'n' is the criteria number being weighted.

$$Wi = \frac{Si}{\sum_{i=1}^{n} Si} \tag{12}$$

A value function was utilized to calculate the overall performance of each end-of-life disposal alternative, which amassed the performance of each criterion into a single overall value. The thesis employed a linear additive function to aggregate the various criterion scores and weights in order to rank the disposal options. (Deshpande et al. 2020). The linear function is expressed by *equation* (13), where 'V(A)' is the overall value function for a particular alternative, 'Wi' is assigned a weight to criteria and 'Vi (Ai)' is the performance of an alternative A on criterion i.

$$V(A) = \sum_i Wi * Vi(Ai) \tag{13}$$

CHAPTER 5

CASE STUDY ON SPAIN

5.1 Introduction

This chapter presents the step-by-step implementation of the conceptual framework on Spain. The organization of this chapter is divided into three sections: introduction to Spain (Section 5.2), data collection (Section 5.3) and results (Section 5.4).

The first section provides a brief overview on Spain in the context of solar photovoltaics and further draws attention to the rationale behind choosing Spain for the application of the framework. Moving further, the key details pertaining to data collection for the PV waste flow, life cycle assessment, economic assessment and social evaluation are outlined in the second section. The third section finally entails the outcomes or the results through the implementation of the conceptual framework.

The elaboration on the results and the pertaining implications are outlined in detail in Chapter 6.

5.2 Introduction to Spain

Spain has historically been among the first countries that led the solar photovoltaic development (Santos & Alonso-García 2018). From 2007 onwards, there was an aggressive solar energy bonus policy that enabled an exponential 300 percent year-on-year increase in PV production (Movilla et al. 2013). By 2011, Spain had the second highest solar PV installed capacity in the world (Prieto & Hall 2013), which began to decelerate significantly due to the multi-year Spanish economic crisis (Mahalingam & Reiner 2016; Fernández-González et al. 2020). Despite the slide down in the leadership position, Spain still is among the top five solar photovoltaic energy producers in Europe and the top ten in the world (IEA 2020), with yet another steep upward trajectory in the last few years (OurWorldinData 2021).

Taking into consideration the geographical location as well, Spain has the advantage of being one of the ideal countries for solar PVs in Europe as it receives a higher number of hours of solar radiation than Germany, which is the largest producer of photovoltaic energy in Europe (Carrión et al. 2008; Fernández-González et al. 2021). The geographical aspect, combined with the Spanish government's renewable energy-friendly policies, especially towards solar PV (Ordóñez et al. 2022), indicates a bright future for photovoltaics in Spain.

The favourable climatic conditions coalesced with the rapid increase in solar photovoltaic installations stipulate an extraordinary awareness and understanding of end-of-life solar PVs and the associated waste. Moreover, the disproportionate growth in solar PV deployment between 2007 and 2008 also means that Spain will be among the initiatory countries that would encounter significant amounts of end-of-life PV waste (Santos & Alonso-García 2018).

Considering the following four points, Spain was deemed as the perfect choice for implementing the conceptual framework: 1) growth potential of solar PV waste, 2) Spanish government's solar PV-related incentives, which means a continual increase in solar PV deployment 3) EU's WEEE directives (Waste electrical and electronic equipment), which means that Spain is bound to at least meet the minimum EU WEEE thresholds and 4) lack of multi-dimensional sustainability studies that are Spain-centric, in the context of end-of-life solar PV.

5.3 Data collection

Collecting data was indispensable in forecasting the waste flow, life cycle impact assessment, economic evaluation and social assessment. For this reason, careful scrutiny of data was carried out to ensure the accuracy and relevance of the inputted data.

5.3.1 Data collection for PV waste flow

The year-by-year PV installation data between 2005 and 2021 was utilized to project the corresponding waste in the future (first phase of PV waste flow analysis). The annual and cumulative PV installation in MW can be observed in Figure 5.1 (OurWorldinData 2021; Statista 2022a).

For the second period (2022 to 2035), three distinct PV growth rate scenarios were considered: 6 percent, 8 percent and 10 percent per annum. The reason for incorporating three different sub-scenarios was to evaluate the fluctuation in PV penetration due to various reasons and to provide a broader range of choices for the forthcoming studies. The assumption of growth rates was based on the projected solar PV installation targets in 2025 and 2030 (Statista 2022b).

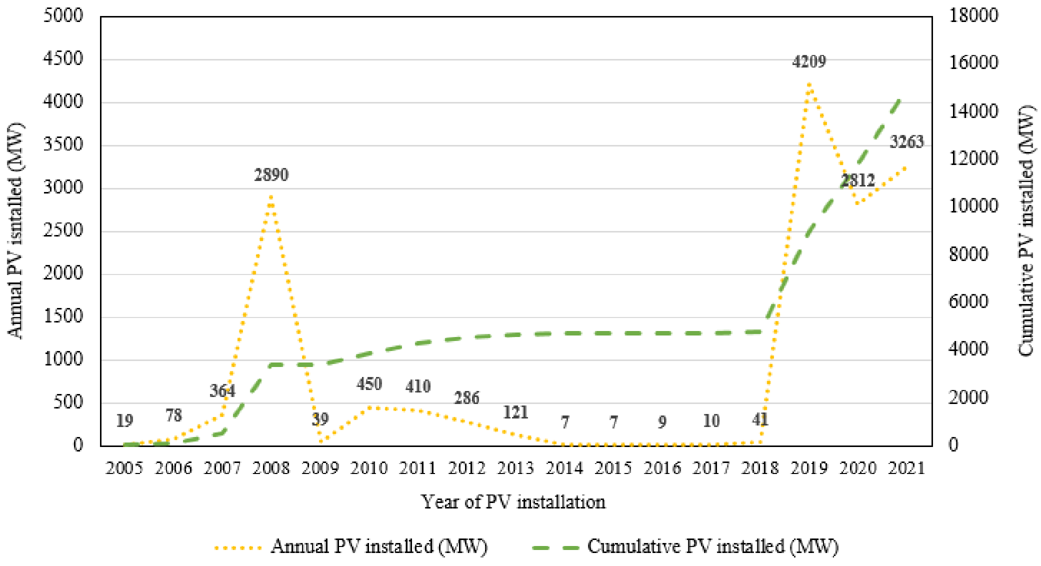

Figure 5.1. Annual and cumulative PV installations (2005 – 2021)

The average material composition and the corresponding recovery rate required for estimating the PV waste inventory are tabulated in Table 5.1.

Table 5.1. Average material composition and recovery rate for a crystalline silicon PV panel

Material	*Proportion (%)*	*Recovery Rate (%)*
Glass	65.4	95
Aluminium	16.5	99.7
EVA	6.5	100
Silicon	0.791	99.9
Copper	0.731	100
Tin	0.0000052	32
Lead	0.00467	96
Zinc	0.00000781	27
Silver	0.0577	95
Steel	9.51	95
Magnesium	0.52	33
Titanium	0.0000052	52
Nickel	0.00106	41

5.3.2 Data collection for environmental assessment

The life cycle inventory data for scenarios 2 – 4 are summarized in Table 5.2, Table 5.3 and Table 5.4. The data provided in the tables above is regarding a functional unit of 1 ton of end-of-life PV panel waste and was scaled by a factor of 10,000. Background data such as impacts due to transportation, landfill and incineration etc., were acquired from the Ecoinvent database (Ecoinvent 2013). Also, the background activities are referred to as the market average processes because an attributional modelling approach has been employed for the recycling process impacts (Commission 2010).

For scenario 2, the relevant input and output parameters were obtained from Latunussa et al. (2016). The foreground data on the laminated glass recycling facility

(LGRF) was acquired from a survey by IEA's Task Force 12 on Maltha glass recyclers in Belgium Wambach et al. (2017). The input and output statistics for the full recycling (FRELP) were obtained from SASIL: developers of FRELP process Latunussa et al. (2016).

Table 5.2. LCI data for scenario 2

Input/Output	*Unit*	*Quantity*
Input		
PV panel waste	ton	1
Electricity	kWh	62.5
Diesel	L	1.14
Output (recovered materials)		
Alumnium	kg	171
Copper	kg	3.3
Output (energy recovery)		
Electricity from incineration	MJ	19.16
Heat from incineration	MJ	28.86

Table 5.3. LCI data for scenario 3

Input/Output	*Unit*	*Quantity*
Input		
PV panel waste	ton	1
Electricity	kWh	62.5
Diesel	L	2.5
Output (recovered materials)		
Glass	ton	0.640
Copper	ton	0.0018901
Aluminium	ton	0.13505
Output (other)		

Incineration	ton	0.16
Landfill	ton	0.059

Table 5.4. LCI data for scenario 4

Input/Output	Unit	Quantity
Input		
PV panel waste	ton	1
Electricity	kWh	113.55
Diesel	L	1.14
Nitric acid	ton	0.00708
Water	ton	0.30971
Calcium hydroxide	ton	0.0365
Output (energy recovery)		
Electricity	kWh	248.84
Thermal energy	MJ	502.84
Output (recovered materials)		
Aluminium	ton	0.18265
Glass	ton	0.686
Silver	ton	0.0005
Silicon	ton	0.03468
Copper	ton	0.00438
Output (disposal to landfill)		
Contaminated glass	ton	0.014
Fly ash	ton	0.002
Sludge	ton	0.05025
Liquid waste	ton	0.30613
Output (air emission)		
NOx	ton	0.002

5.3.3 Data collection for economic analysis

The vital financial variables essential to conducting the economic analysis are tabulated in Table 5.5. The input parameters such as inflation rate, interest rate, capital ratio, cost of electricity, local minimum wage etc., are directly in the context of Spain. Other variables such as emission, unitary transportation, raw material cost (water, nitric acid, calcium hydroxide), are global or European averages.

Table 5.5. Summary of key financial variables

Variable	*Value*	*Reference*
Inflation rate	1.46 %	(Talavera et al. 2019)
Equity capital ratio	5.9 %	(Trading Economics 2022)
Interest rate	5.7 %	(Talavera et al. 2019)
Local minimum wage	1000 Eur/month	(Statista 2022c)
Unitary transportation cost	0.27 Eur/ton.km	(Faircloth et al. 2019)
Unitary emission cost (transportation)	0.002 Eur/ton.km	(Liu et al. 2020)
Salvage value	5 percent	(Liu et al. 2020)
Landfill cost	40 Eur/ton	(CEWEP 2021; KPMG 2022)
Equipment maintenance cost	2 % of depreciation	(Liu et al. 2020)
Cost of diesel	1.9 Eur/litre	(GlobalPetrolPrices.com 2022)
Cost of electricity	0.106 Eur/kWh	(GlobalPetrolPrices.com 2022)
Cost of water	1.95 Eur/m3	(Water News Europe 2021)
Cost of nitric acid	394.8 Eur/ton	(Chemanalyst 2022)
Cost of calcium hydroxide	340 Eur/ton	(Chemanalyst 2022)
Sales benefit from recovered materials	Glass (67.3 Eur/ton); Al (1598 Eur/ton); Si (5666 Eur/ton); Cu (5386 Eur/ton); Ag (553660 Eur/ton)	(Faircloth et al. 2019; Liu et al. 2020; Markert et al. 2020)
Period of investment	15 years	Author’s assumption

5.4 Results

This sub-section includes the implementation of the conceptual framework on Spain and is further split into the following sub-sections: 1) PV waste flow, 2) findings of life cycle assessment, 3) economic evaluation, 4) social assessment and 5) multi-criteria decision analysis.

5.4.1 PV waste flow

5.4.1.1 Waste projection from 2035 to 2051

The results of early and regular loss schemes through the lens of the Weibull function can be seen in Figure 5.2. It can be observed that from the point of a nominal lifetime (i.e., 30 years), there is an opposite response for early loss and regular loss, which is basically in accordance with the chosen shape factor. As a result, from 30 years onwards, the regular loss scheme has a higher probability of loss than early loss.

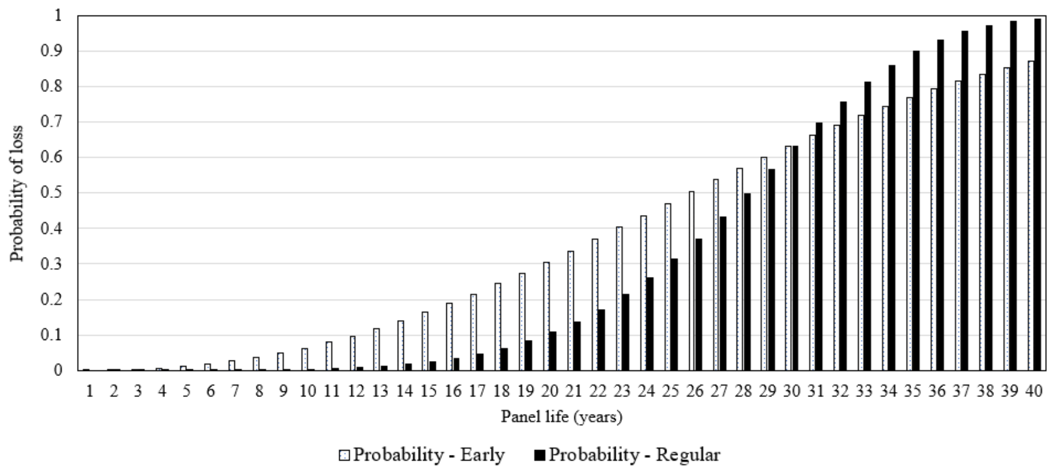

Figure 5.2. Probability of loss for early and regular loss scheme

The cumulative decommissioning of solar PV panels over a 30-year period is depicted in Figure 5.3. Predicated on the findings of the fixed loss scheme, the amount of end-of-life PV panels is non-existent until 2035, but in 2038 there is an unprecedented increase due to the Spanish PV installation boom in 2008. Post-2008 moratorium indicates a substantial reduction in end-of-life PV waste from 2039 to 2048, until 2049 when the PV waste stream is substantial.

For the early loss scheme, a significantly higher amount of end-of-life PV waste is envisaged initially in comparison to the regular loss because of the assumption that various factors can lead to reduced life of a solar PV panel. Taking into account the degradation rate in the early loss scheme, as illustrated in Figure 5.4, shows that amount of PV panel waste for the early loss scheme is higher if the degradation rate is included in the analysis.

The regular loss scheme has a lower waste estimation per annum till 2038. From 2039 onwards, the waste pertaining to the regular loss scheme exceeds that of early loss. In 2048, the waste estimation peaked at 963207 tons for the 30-year period. Due to significant fluctuations in the PV panel installations per annum from 2005 – 2021, an identical representation of early and regular loss schemes in reference to the Weibull distribution curve could not be obtained.

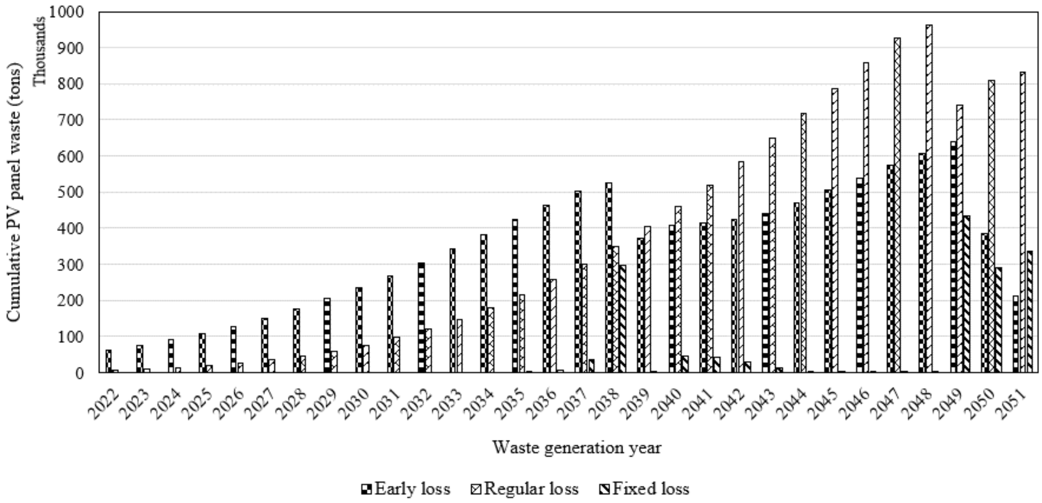

Figure 5.3. Cumulative waste estimation of EOL solar PV panels (2022 – 2051)

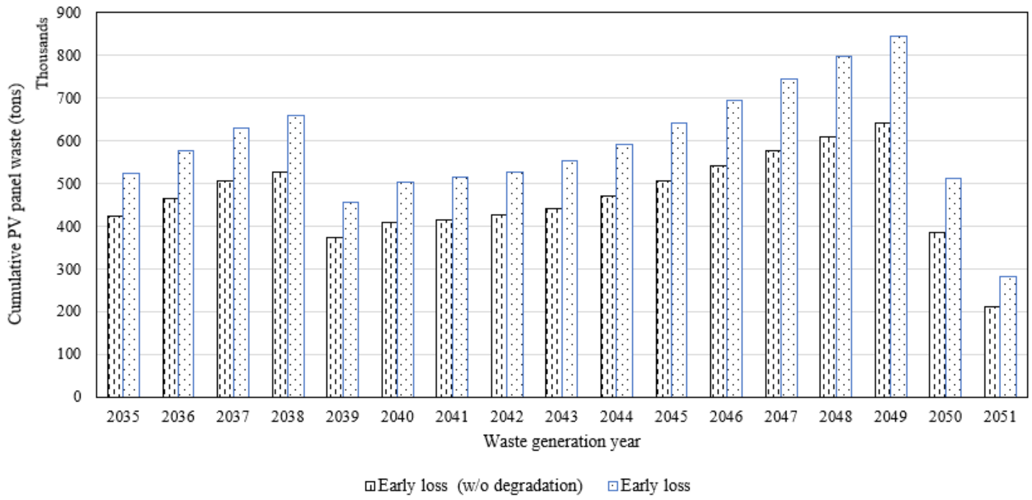

Figure 5.4. Cumulative PV waste for early loss with & without degradation rate

Moving further, the composition of PV waste was determined for each of the three loss schemes from 2035 to 2051, also demonstrated in Figure 5.5, Figure 5.6 and Figure 5.7. In order to do that, the percentage composition of each material was multiplied by the amount of waste in tons in that specific year. The end-of-life solar PV waste comprises the following constituents: glass, aluminium, EVA, silicone, copper, tin, lead, zinc, silver, steel, magnesium, titanium and nickel.

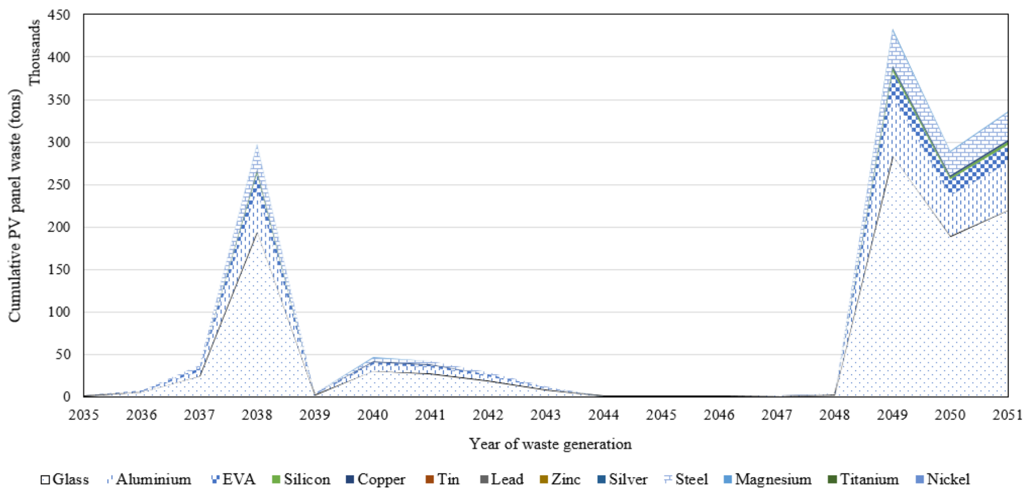

Figure 5.5. Composition of PV waste – fixed loss scheme (2035 – 2051)

By analyzing the composition of the three loss schemes, it can be observed that glass is the largest constituent of the PV waste, followed by aluminium and then steel. These three materials are cumulatively responsible for over 90 percent of end-of-life solar PV waste.

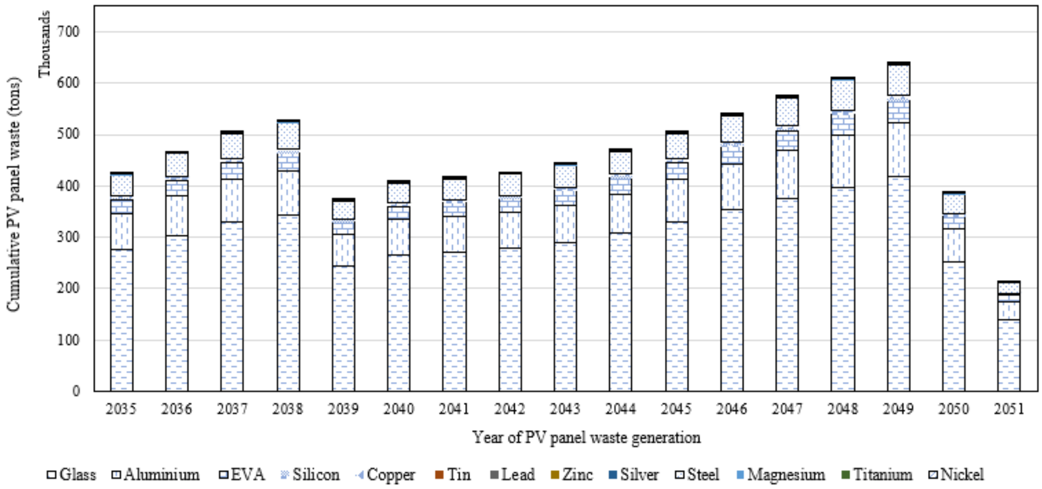

Figure 5.6. Composition of PV waste – early loss scheme (2035 – 2051)

From this point onwards, the end-of-life waste for the fixed loss scenario was only accounted for because PV panels can be associated as a durable commodity. This means that PV panels generally have a low failure rate, and therefore, only the waste at the end of their operational life (i.e., 30 years) will be considered. Not to forget that this assumption is reasonable, and evaluating waste projection solely through the fixed loss scheme is still robust (Mahmoudi, Huda, & Behnia 2019).

The total amount of materials recovered in the time period 2035 to 2051 was separated into the following categories: critical substances, precious metals, base and special metals, hazardous metals, other metals and other materials. Obtaining the average recovery yields of each material from the literature and combining that with the amount of waste, the total recovered waste per material was predicted.

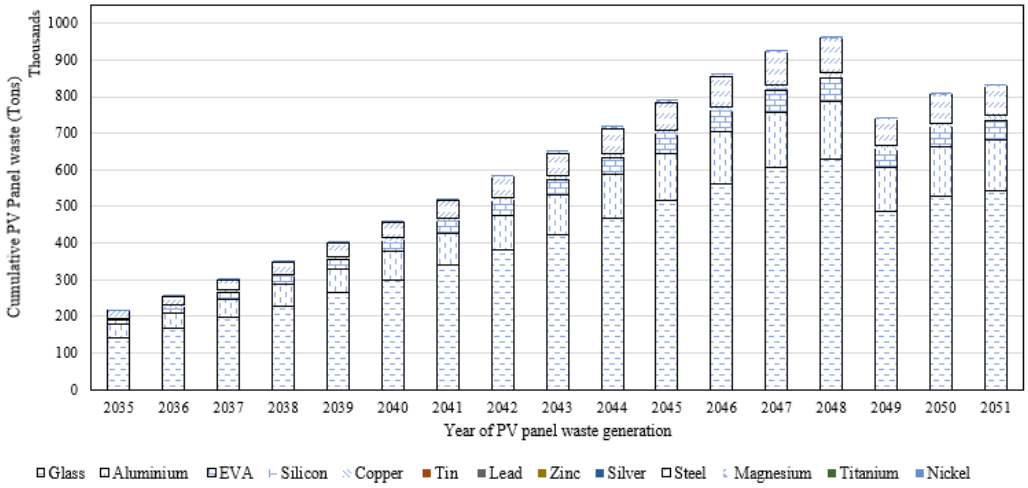

Figure 5.7. Composition of PV waste – regular loss scheme (2035 – 2051)

By dividing the recovered waste by total waste, it was estimated that amount 95.9 percent of the waste can be injected back into the economy. The percentage-wise distribution of critical substances, other metals, hazardous metals, base and special metals and precious metals can be observed in Figure 5.8. Base and special metals account for 61.29 percent of the total end-of-life PV waste, followed by 36.64 percent of other metals. Precious metals and hazardous metals collectively are responsible for less than 0.25 percent of the total waste.

Table 5.6. Recovery yields and cumulative waste recovery estimation (2035 – 2051)

	Material	*Waste (t)*	*Recovered Waste (t)*
Precious metal	Silver	8.92E+02	8.48E+02
	Aluminium	2.55E+05	2.54E+05
	Copper	1.13E+04	1.13E+04
	Nickel	1.64E+01	6.72E+00
	Titanium	8E-02	4E-02
	Tin	8E-02	3E-02
Base and special metals	Zinc	1.2E-01	3E-02
Hazardous metal	Lead	7.22E+01	6.93E+01

Critical substances	Magnesium	8.04E+03	2.65E+03
Other metals	Silicone	1.22E+04	1.22E+04
	Steel	1.47E+05	1.4E+05
Other material	EVA	1.01E+05	1.01E+05
	Glass	1.01E+06	9.61E+05
Total	-	1.55E+06	1.48E+06
Overall recovered waste (%)		95.9	

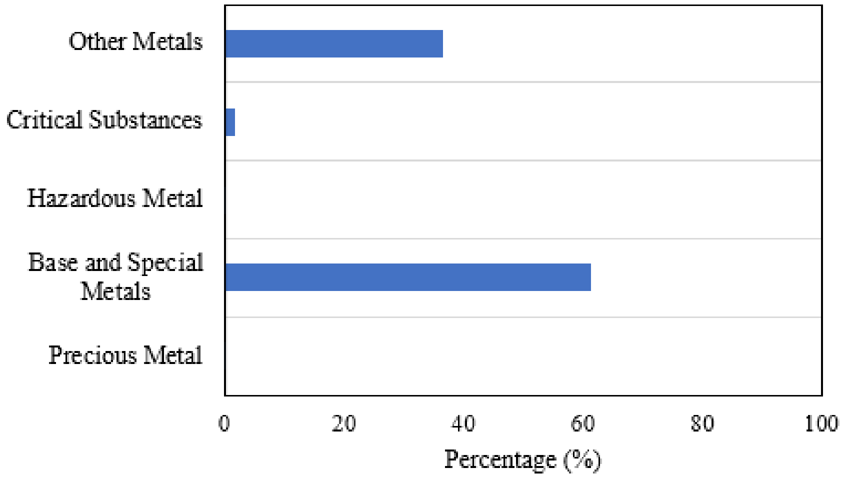

Figure 5.8. Category-wise distribution of PV waste (2035 – 2051)

5.4.1.2 Waste projection from 2052 to 2065

This section's forecasting of end-of-life PV waste projection is based on the PV installations between 2022 and 2035. Due to the unavailability of the exact year-on-year PV growth rate, the following scenarios were assumed: 6 percent growth, 8 percent growth and 10 percent growth. The increase in PV installations has been quite aggressive in the past three years; however, the assumption of the three growth scenarios has been more modest because such drastic increases are not sustainable over a longer time frame.

The increase in waste generation can be observed in Figure 5.9 based on the three growth scenarios. As expected, a higher PV penetration will lead to increased waste, which would require a better and more sustainable waste management mechanism. The cumulative PV capacity and the corresponding PV panel waste in tons for the three growth scenarios are also presented in Table 5.7.

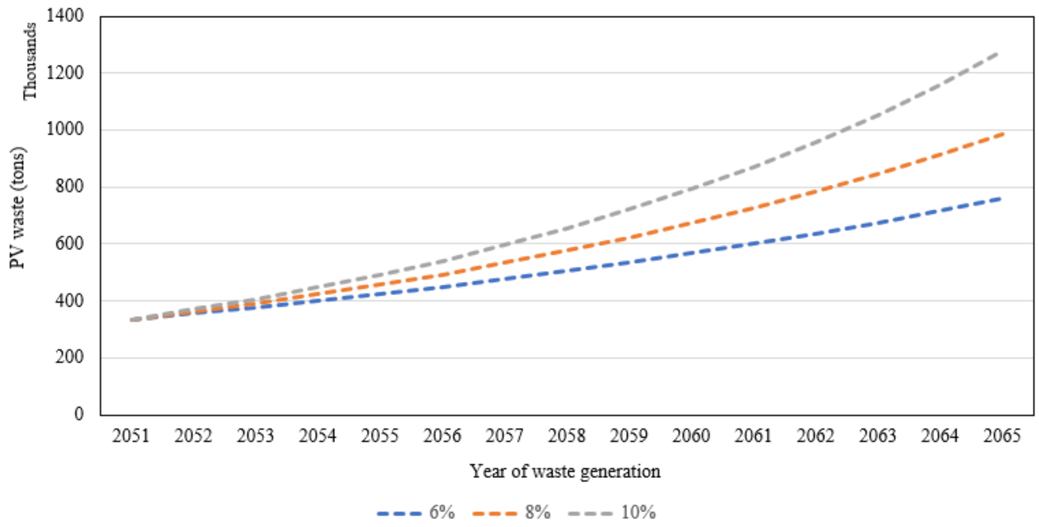

Figure 5.9 Waste generation based on three different growth rates (2051 – 2065)

The total waste between 2052 and 2065 would include significant quantities of precious metals, base and special metals, critical substances, hazardous metals, other metals (steel & silicone) and other materials (EVA and glass). The amount of metal inventory during the time period (2052 – 2065) for the three growth scenarios is summarized in Table 5.8. Other materials account for the highest proportion of PV panel waste, followed by the base, special metals, and other metals.

Table 5.7. Cumulative capacity and PV panel waste based on the growth rates

PV growth rate (%)	*Cumulative capacity in 2035 (MW)*	*PV panel waste in 2065 (tons)*
6	8.77E+04	7.60E+05
8	1.00E+05	9.87E+05
10	1.20E+05	1.28E+06

Table 5.8. Category-wise distribution of PV waste (2052 – 2065)

	6% (kiloton)	*8% (kiloton)*	*10% (kiloton)*
Precious metal	4.32	5.07	5.97
Base & special metals	1290.12	1514.60	1782.19
Hazardous metal	0.35	0.41	0.48
Critical substances	38.93	45.71	53.78
Other metals	771.21	905.40	1065.36
Other materials	5382.94	6319.61	7436.11

5.4.2 Findings of life cycle assessment

From a total of 18 midpoint indicators, the following 6 indicators were included in the results and further in determining the overall sustainability score in Section 5.7: freshwater eutrophication, climate change, terrestrial acidification, human toxicity, fossil depletion and ozone depletion. Based on the review of other studies, these indicators were seen as more relevant to this research (Deshpande et al. 2020; Ganesan & Valderrama 2022).

For Scenario 1, transport and disposal to landfill (represented by waste) are the only two relevant factors, also shown in Figure 5.10. The impact of transportation is more dominant across all the impact assessment categories, demonstrating that the disposal at a landfill has lower environmental impacts than transporting the waste to a dumping site. The contribution of transportation to the overall eutrophication, climate change and human toxicity is more than 70 percent.

Scenario 2 includes transportation, waste disposed to landfill, and recovery of aluminium from the frame and polymer and copper from the cables. Moreover, it also entails the impact of diesel and electricity, characterized under the category ‘Other’ in Figure 5.11. As expected, the recovery effect (aluminium and cables) is a net positive, representing the negative direction. The impact of transportation is around 57 percent or more for the following midpoint indicators: freshwater eutrophication, fossil depletion, ozone depletion and climate change, whereas, for the other two indicators, the impact of transportation is significantly lower.

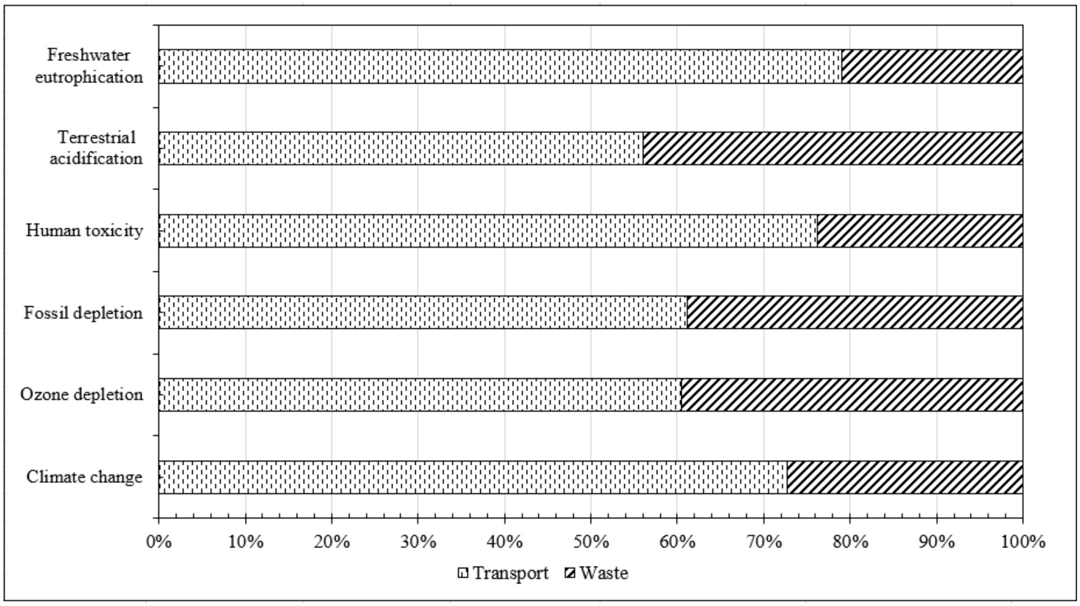

Figure 5.10. Contribution of transport & waste – Scenario 1

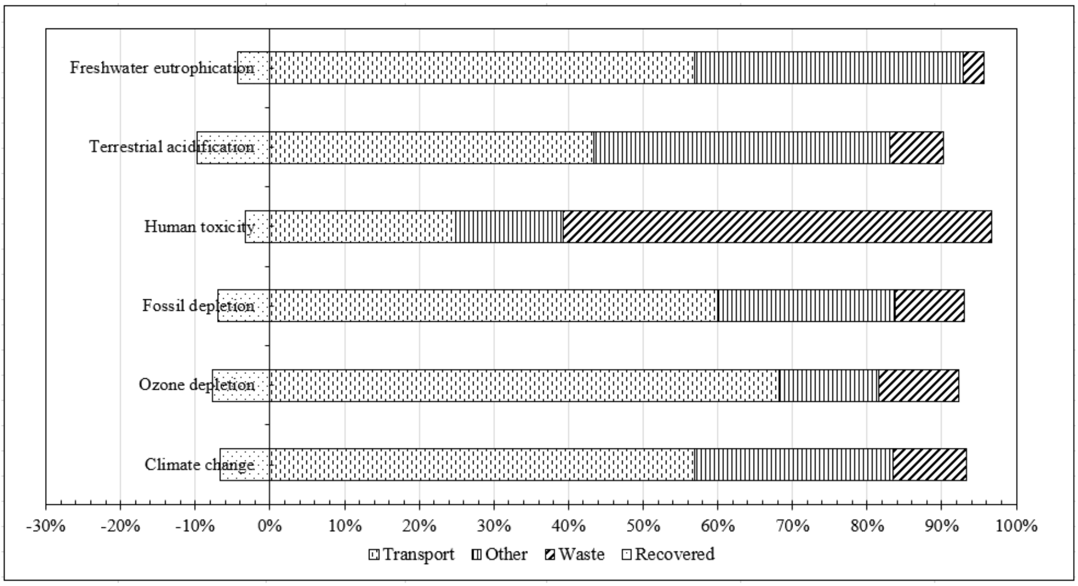

Figure 5.11. Contribution of transport, other, waste & recovered - Scenario 2

The contribution to human toxicity is the highest by waste disposal in landfills, followed by transportation. The impact of waste on the other impact categories is significantly lower.

Scenario 3 represents glass recycling (LGRF) and includes the contribution of transport, credit due to aluminium, copper, glass and energy recovery, and electricity and diesel, which is characterized under the category ‘Other’. Like Scenario 2, the recovery is represented in the negative direction, which means a net positive. The overall positive obtained from copper and energy recovery is extremely small and, therefore, is not visible in Figure 5.12. However, the impact of aluminium recovery is a bit more visible, whereas the impact of glass recovery is most evident.

The impact of transportation on the 6 midpoint impact categories is significant in Scenario 3. As seen in Figure 5.12, transport contributes 67 percent, 78 percent and 81 percent to the overall human toxicity, climate change and fossil depletion, respectively. The cumulative impact of diesel and electricity is the maximum for ozone depletion, followed by eutrophication and acidification.

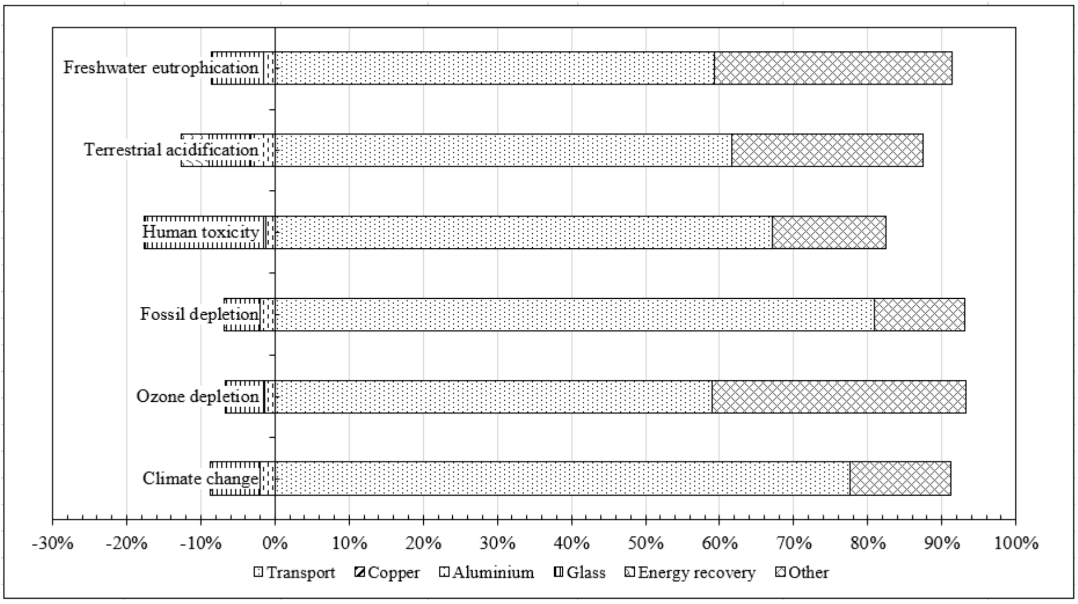

Figure 5.12. Contribution of 6 distinct parameters – Scenario 3

For Scenario 4, the contribution of transportation, waste, and input materials characterized under the category ‘Other’ and recovery of copper, aluminium, glass, silicon, silver and energy is demonstrated in Figure 5.12. Since this scenario focuses on full recycling, the impact of all midpoint indicators is towards the left of the x-axis, representing an overall positive. The impact of specific categories such as the recovery of energy, copper, aluminium and glass are not clearly visible in Figure 5.12 because of their insignificant overall impact for each midpoint category.

On the other hand, the impact of silver recovery on human toxicity, acidification, and eutrophication is the highest compared to the recovery of other materials. Silicon has the highest positive impact on climate change, ozone depletion and fossil depletion. Since the waste disposal at the landfill is extremely less, its contribution to the midpoint categories is not evident in Figure 5.13.

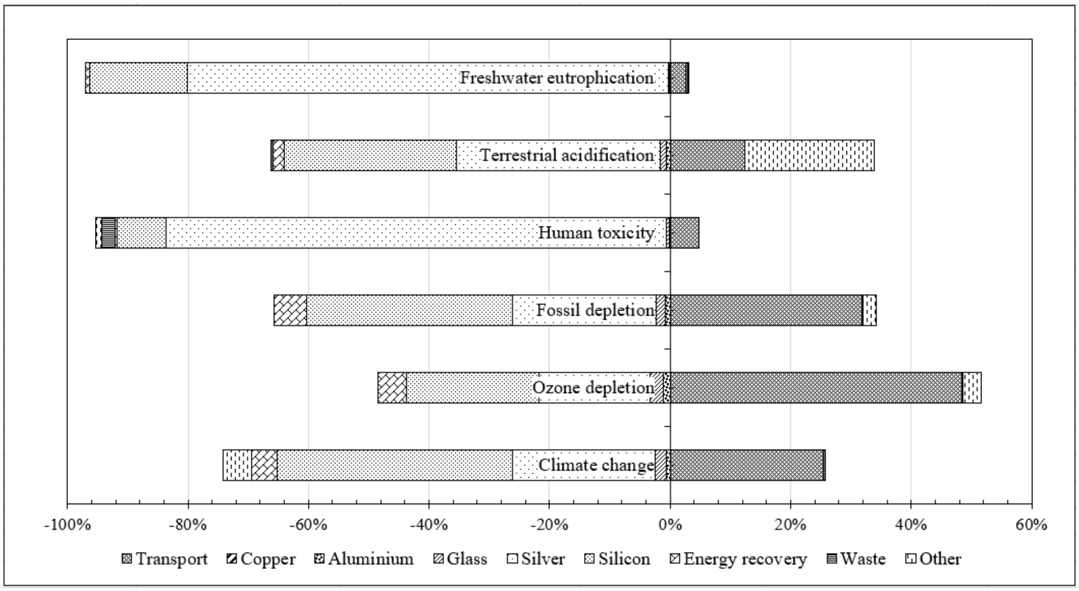

Figure 5.13. Contribution of 9 distinct parameters – Scenario 4

5.4.3 Economic evaluation

The economic evaluation broadly depends on the cash inflows and outflows. As mentioned in the previous section (conceptual framework), cash outflows include collection and transportation costs, waste disposal costs, raw material costs, total labour costs (worker wages and management cost), depreciation costs and financing costs. Cash inflow comprises sale benefits from recovered materials and energy recovery.

The collection & transportation cost is the maximum for scenario 4, followed by scenario 3, as seen in Figure 5.14. Since the amount of waste is kept unchanged for each scenario, the total distance travelled is the only variable parameter. The system boundary of scenario 4, includes multiple operations such as incineration for energy recovery and disposal of hazardous and non-hazardous waste to landfill; therefore, the distance travelled is the highest. The total transportation cost for 10,000 tons of PV waste is about 2.2 million euros for scenario 4. Subsequently, for scenario 3, the cost of transportation is approximately 1.2 million euros and 275,000 for scenario 1 and 2.

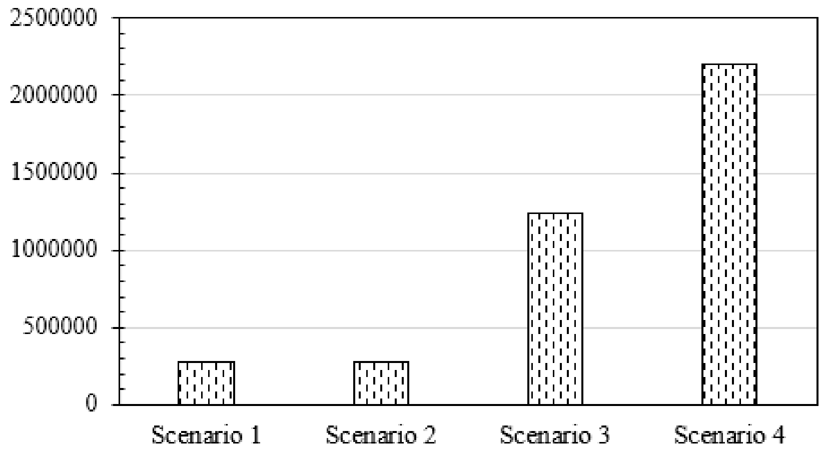

Figure 5.14. Cost of transportation (& collection) for 4 scenarios

As expected, the cost of waste disposal is the highest for scenarios 1 and 2, whereas scenario 3 incurs the lowest waste disposal cost. Raw material cost is not applicable for scenario 1 because the entire waste is landfilled, whereas it's the highest for scenario 4. Since the extent of recycling is the maximum in this scenario, it makes sense that scenario 4 incurs a higher raw material cost than the other scenarios. Total labour cost implies both worker wages and salaries of administrative personnel. The labour cost is almost the same for scenarios 1 and 2, whereas it is higher for scenario 3 and significantly higher for scenario 4. Since scenario 4 is labour-intensive and more complex than other scenarios, it is logical that it would employ more workers and administrative personnel. The comparison between the waste disposal cost, raw material cost and total labour cost are illustrated in Figure 5.15.

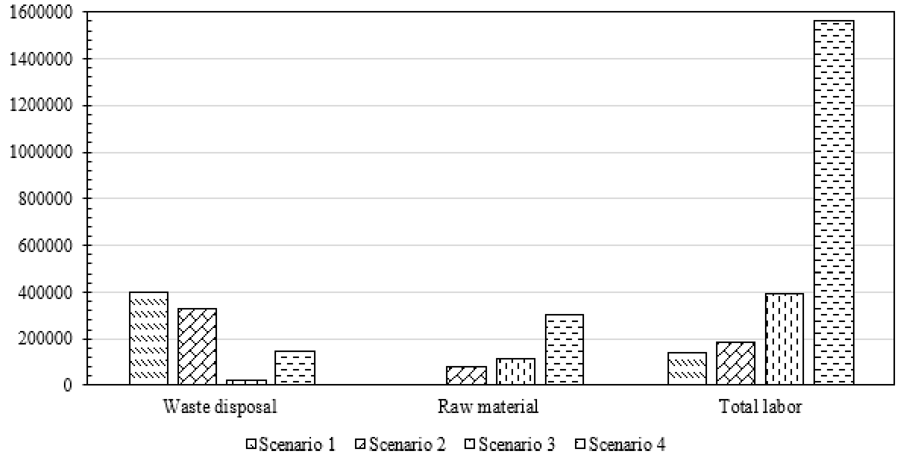

Figure 5.15. Cost of waste disposal, raw material, total labour for 4 scenarios

Moreover, the cost breakdown for raw materials for 1 ton of PV waste is illustrated in Figure 5.16. Since scenario 4 involves the maximum degree of recycling, its raw material cost per ton is also the highest. Scenario 3 employs considerably fewer raw materials, followed by scenario 2. Diesel and electricity are common raw materials for scenarios 2, 3 and 4. Calcium hydroxide accounts for about 41 percent of the raw material cost in scenario 4, followed by electricity cost utilizing 40 percent.

The depreciation and financing cost was assumed to be applicable in scenarios 2 and 4 only. The reason is that scenario 1 is a direct landfill and scenario 3 is glass recycling which is done in batches, and no particular investment needs to be done for end-of-life PV recycling. Therefore, scenario 3 incurs no depreciation, equipment maintenance and financing cost (Deng et al. 2019). The depreciation and equipment maintenance cost was significantly less (less than 5000 euros for both) for scenario 2. Since scenario 4 involves complex and sophisticated equipment and a high investment cost, its depreciation cost, financing cost, and equipment maintenance cost are worth accounting for and are illustrated in Figure 5.17.

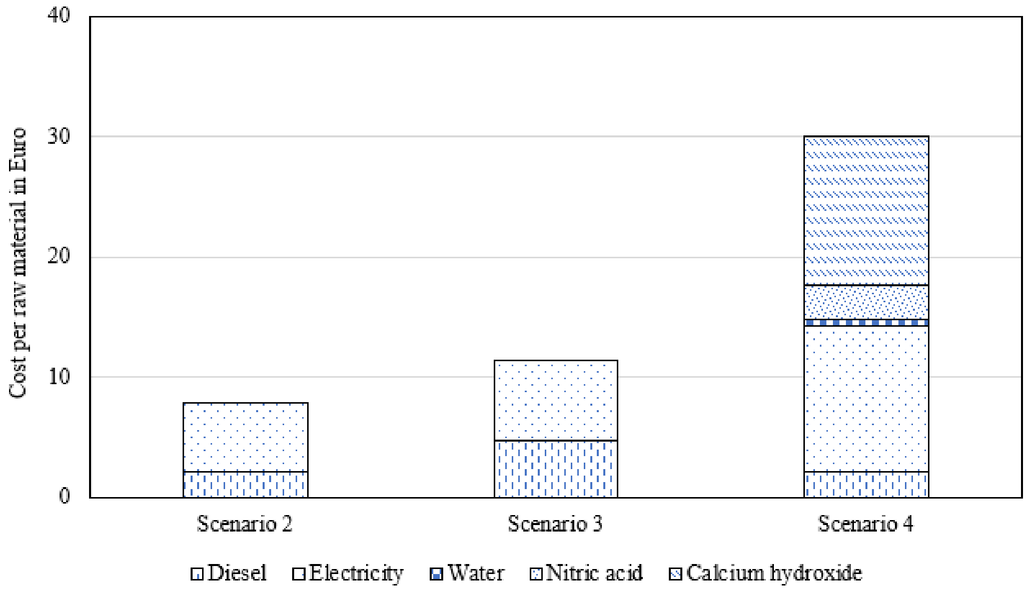

Figure 5.16. Cost breakdown of raw materials for 1 ton PV waste

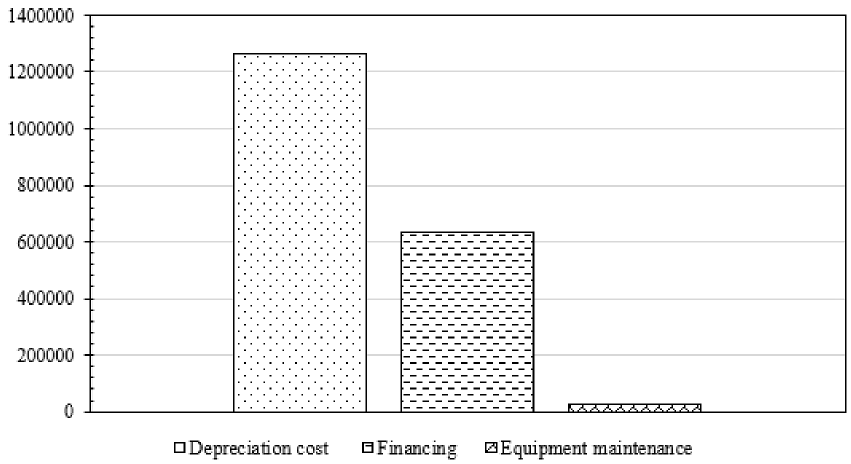

Figure 5.17. Cost of depreciation, financing & equip maintenance for scenario 4

The sale benefit is none from scenario 1 as it is completely disposed of in the landfill. For scenario 2, where aluminium and cables are further sent for recycling, the sale benefit is 2.9 million euros. Scenarios 3 and 4 receive sale benefits from both recovered materials and energy recovery. However, the cash inflow from scenario 4 is significantly higher due to its full recycling characteristic. Therefore, the total sale benefit from scenario 3 and scenario 4 is about 3.8 million euros and 8.6 million euros, respectively. The sale benefit for scenarios 2, 3 and 4 are illustrated in Figure 5.18.

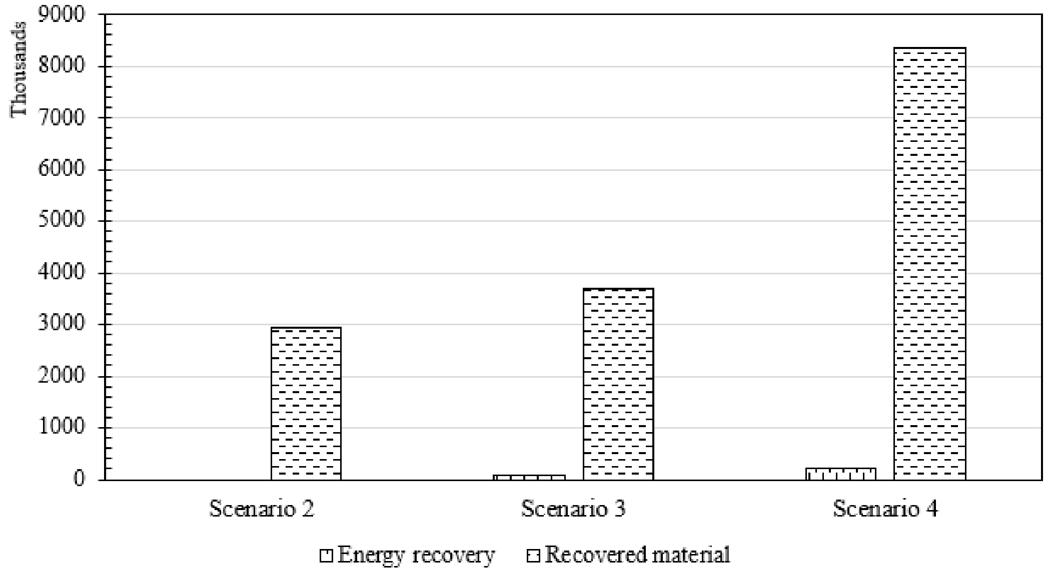

Figure 5.18. Sale benefit from energy recovery & recovered materials

5.4.4 Social assessment

The performance of the four disposal scenarios against the social indicators is summarized in Table 5.4. The corresponding values for local job creation for scenario 1 and scenario 4 were obtained from the literature. The multiplication factor for scenario 3 was assumed to be similar to that for decentralized bulking because of similar process flow, whereas the factor for scenario 2 was based on the author's judgement.

Scores of 0, 0.25, 0.5 and 1 were assigned for the remaining indicators. Scenario 4 had a score of '1 for all the indicators other than for health and safety of workers, where it received a score of '0.5'. Scenario 3 was awarded '1' for consumer awareness and public participation, whereas, for other indicators, a score of '0.5' was dispensed. Scenario 1 has a score of '0' for all indicators except for the health and safety of workers, where it received a score of '0.5'.

Scenario 2 does not contribute to consumer awareness, public participation, or energy security. A ranking of 0.25 was allocated for the contribution of technology to economic progress because some of the material (cable connector and aluminium) was sent to the recycler.

Table 5.6. Performance of indicators against the disposal scenarios

Indicator	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*
Contribution of the technology to economic progress	0	0.25	0.5	1
Energy security	0	0	0.5	1
Health & safety of workers	0.25	0.25	0.5	0.5
Local job creation	2.8	4.2	9.2	18.4
Consumer awareness and public participation	0	0	1	1
Eco-industrial partnership	0	0	0.5	1

5.4.5 Multi-criteria decision analysis

Two distinct questionnaires were prepared and distributed among solar photovoltaic experts via personal invitations on both email and LinkedIn. The first questionnaire was circulated among experts globally, whereas the second questionnaire was only for solar PV pundits from Spain. In total, 47 responses were garnered for questionnaire 1 and 15 responses for questionnaire 2.

The first questionnaire included the following: 1) respondent's country, 2) importance of the three sustainability dimensions (economic, environmental, social) on a scale of 1 to 5 (with 1 being the least important and 5 being the most important), 3) importance of the included social indicators (choosing between the following options: not important, less important, important, very important and most important), 4) impact of included drivers on end-of-life management (low, moderate, high or not applicable), 5) impact of included barriers on end-of-life management (low, moderate, high or not applicable) and 6) impact of included enablers on end-of-life management (low, moderate, high or not applicable).

In the second questionnaire, the following questions were included: 1) importance of the three sustainability dimensions (economic, environmental, social) on a scale of 1 to 5, 2) importance of the included economic indicators, 3) importance of the included environmental indicators, 4) importance of the included social indicators, 5) stakeholders with the most responsibility for recycling end-of-life solar PV panels on a scale of 1 to 3 (with 1 representing minimum responsibility and 3 meaning most responsibility) and 6) stakeholders with the most responsibility for regulations relevant to end-of-life solar PV panels on a scale of 1 to 3.

Since social sustainability has been the most neglected aspect of sustainability, the reason for including the question pertaining to social indicators in both the questionnaires was to later compare the responses of solar PV experts in Spain to the rest of the world in order to get a broader and a generalized perspective. The same was the reason for including the question about the importance of each sustainability dimension in both the questionnaires. Further information on the questionnaire constituents can be found in the Appendix.

Based on the questionnaire responses, the mean, standard deviation and weight of the sustainability dimensions and assessment indicators were computed and are summarized in Table 5.7. Environmental sustainability has a weight of 0.34, whereas economic and social sustainability received a weight of 0.37 and 0.29, respectively. In the environmental assessment criteria, climate change and human toxicity have the highest weight of 0.21 each, whereas acidification and human toxicity both have the lowest weight of 0.14. The deviation in the economic assessment criteria was the least (among environmental, economic and social), with revenue generation being assigned a weight of 0.18 and the remaining criteria receiving a weight of either 0.20 or 0.21.

Table 5.7. Mean, standard deviation and weight of sustainability dimensions and assessment indicators

Criteria	*Mean*	*SD*	*Weight*
Sustainability Dimensions			
Environmental	4.00	1.06	0.34
Economic	4.45	0.74	0.37
Social	3.48	1.09	0.29
Environmental			
Climate change	3.87	1.25	0.21
Ozone depletion	2.93	1.10	0.16
Fossil depletion	3.20	1.01	0.17
Terrestrial acidification	2.67	1.11	0.14
Eutrophication	2.67	0.98	0.14
Human Toxicity	3.87	1.25	0.21
Economic			
Transportation cost	3.67	0.90	0.22
Total labor cost	3.20	0.94	0.19
Processing cost	3.40	1.12	0.20
Disposal cost	3.47	1.13	0.21
Revenue generation	3.13	1.13	0.19
Social			
Contribution to economic progress	3.20	1.21	0.15
Energy security	3.87	0.99	0.19
Health & safety of workers	4.07	0.96	0.20
Local job creation	3.87	0.83	0.19
Consumer awareness and public participation	3.20	1.08	0.15
Eco-industrial partnership	3.45	1.37	0.12

Among the criterion for social sustainability, the health and safety of workers were assigned the maximum weight of 0.20, followed by energy security and local job creation, both receiving a weight of 0.19. The eco-industrial partnership had the lowest weight in social assessment criteria of 0.12.

The MCDA model for the proposed assessment of EoL PV scenarios is presented in Figure 5.19.

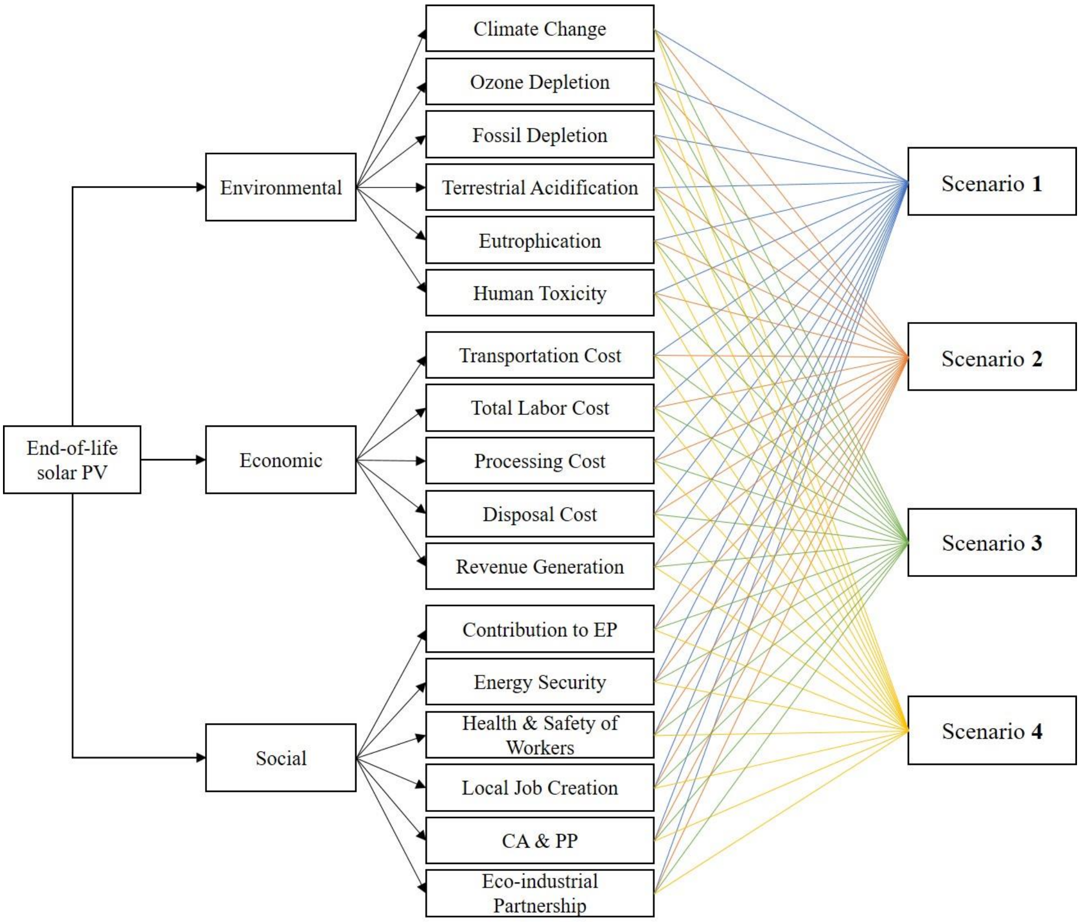

Figure 5.19. MCDA model for end-of-life solar PV management

The multi-criteria decision model computed each scenario's environmental, economic and social sustainability score. Observing the radar graph in Figure 5.20, it can be confirmed that scenario 4 is the least economically sustainable under the present circumstances, whereas scenario 3 is the best option. The social sustainability score is dominated by scenario 4, followed by scenarios 3, 2 and 1. Scenario 4 is also ideal for environmental sustainability, followed by scenarios 3, 2 and 1.

The scores represented by the radar graph were generated by normalizing the results for every indicator in each sustainability dimension. The extra normalisation step was added because of its apparent advantages, such as data organisation, improving accuracy and bringing the data to a standard scale. The normalized results were multiplied by the indicator weight and later added to compute each end-of-life scenario's environmental, economic and social sustainability score. The aggregated scores were multiplied by the sustainability dimension weight to obtain the overall sustainability score.

As shown in Figure 5.21, scenario 1 has the lowest overall sustainability score, whereas scenario 4 has the highest. The total sustainability score of each scenario is demonstrated in Figure 5.20. Predicating on the final sustainability score, it can be concluded that even though full recycling in scenario 4 is economically expensive (compared to other scenarios), it has the highest overall sustainability score.

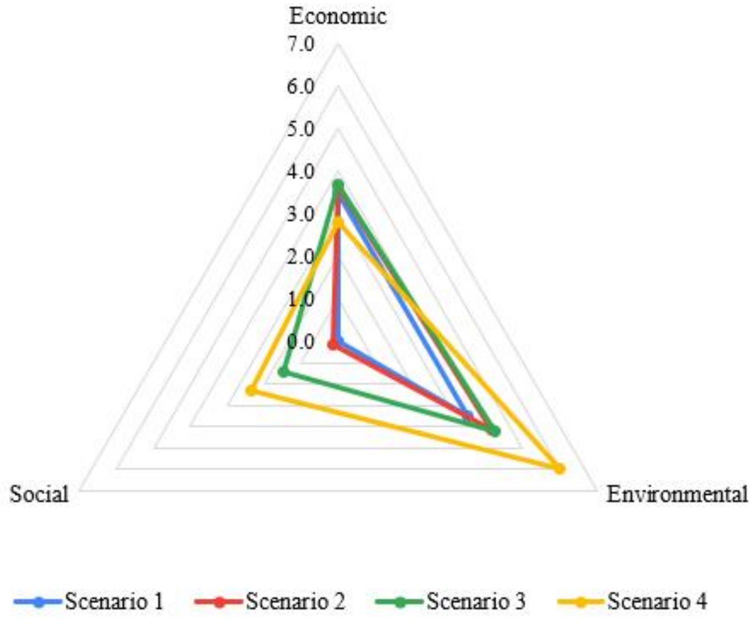

Figure 5.20. Radar graph based on the triple bottom line

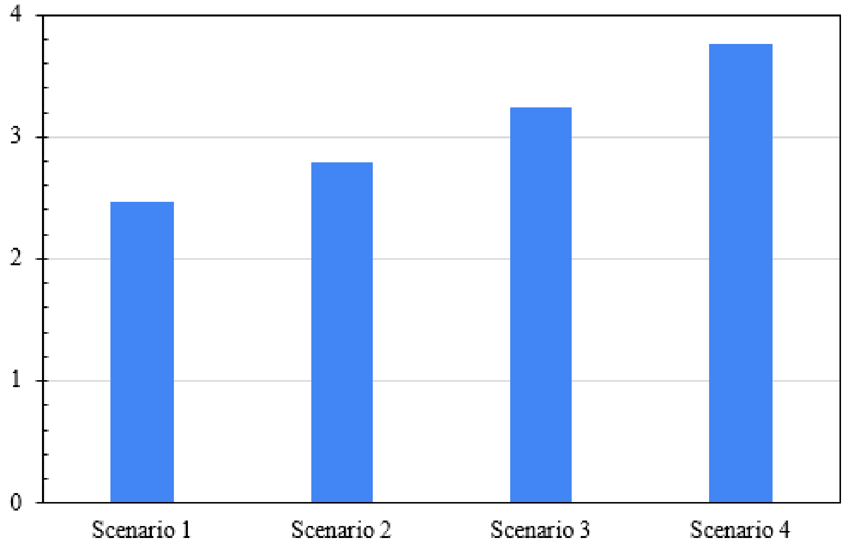

Figure 5.21. Overall sustainability score for each end-of-life scenario

CHAPTER 6

DISCUSSION

6.1 Introduction

This chapter emphasizes the ultimate research step, which is a further elucidation on the implementation of the conceptual framework on Spain. This chapter's organisation is as follows: additional insights on the PV waste flow are outlined in Section 6.2, interpretation of life cycle impact assessment delineated in Section 6.3, followed by Section 6.4, where more details about the economic assessment are provided. Section 6.5 and 6.6 emphasize social evaluation and multi-criteria decision analysis, respectively. Finally, in Section 6.7, an in-depth elaboration on the drivers, barriers and enablers to sustainable end-of-life PV management is provided.

6.2 PV waste flow

The quantity of end-of-life solar PV panels will likely dictate the future of end-of-life solar PV management in Spain. By observing Figure 5.3, a better insight can be derived regarding the timeline for boosting the local PV waste recycling industry. The temporal gap associated with degradation scenarios makes accurate projection of specific PV waste tedious. Having said that, actual data of PV panel installations is still vital to estimate the potential decommissioning year of a solar panel. Establishing a state-of-art monitoring system that documents scrapped PV modules to improve PV waste flow forecasting is indispensable. Better handling of decommissioned PV modules through a proactive approach would make the discarded PV instantly pursuable.

According to recent import data from (Trading Economics 2021), Spain imports certain materials and metals common in solar PVs, such as aluminium, copper, glass and glassware, lead and tin. The economic valuation of these imports adds up to about 2.5 percent of the total import bill, where aluminium import bill is about 5.09 billion dollars (1.2 percent of total imports), copper import bill is close to 2.83 billion dollars (0.66 percent of total imports), glass and glassware import bill is about 2.1 billion dollars (0.49 percent of total imports), lead import bill is about 334 million dollars (0.078 percent of total imports) and tin import bill is about 251 million dollars (0.051 percent of total imports).

Since many materials can be obtained from end-of-life PV waste, PV waste can be considered a secondary mining industry (Gautam et al. 2021). Development and improvement in recovery and recycling techniques will undoubtedly benefit Spain owing to the financial value of materials such as glass, aluminium and copper. Glass and aluminium together account for more than 80 percent of the total PV module weight, which means that recovering and recycling these two materials alone can benefit Spain's national exchequer significantly.

Comparing Spain with other European countries in terms of cumulative PV waste depict that the amount of waste (in tons) in 2040 would be significantly higher in Germany and Italy under both a regular and early loss scenario and lower in Turkey and Ukraine. Quantifying it in numbers, a regular scenario would produce the following amount of PV waste in 2040: 2.2 million tons in Germany, 1 million tons in Italy, 0.46 million tons in Spain, 20 000 tons in Turkey and 50 000 in Ukraine (Santos & Alonso-García 2018).

Stemming from the fact, it can be observed that PV waste generation will be dominated by more established solar PV markets such as Italy and Germany. However, the amount of PV waste in Spain will still be higher than in other European countries, such as France and the United Kingdom, which have higher PV penetration and installations. This is a consequence of the earlier and swifter development of the Spanish solar PV sector, especially during the Spanish installation boom in 2007-2008. The sharp decline in the PV installations after the

Spanish boom can be the primary reason for reduced solar PV waste from the lens of fixed and regular scenarios between 2040 and 2050.

6.3 Environmental

The findings of the life cycle impact assessment correlate pretty well with the results of earlier studies (Vellini et al. 2017; Faircloth et al. 2019; Contreras Lisperguer et al. 2020; Mahmoudi et al. 2020). Despite that, a direct comparison with other LCA studies is not usual because of various reasons such as distinct system boundaries and functional units, aggregated results and implicit assumptions. A general comparison, however, validates that the recycling scenarios are environmentally more sustainable across all impact assessment indicators, concluding that scenario 1 is the most environmentally adverse end-of-life option, whereas scenario 4 is the least.

Lunardi et al. (2018) confirm the importance of high-value recycling by stating that upcycling results in lower environmental impact across all impact indicators. Even though recycling is energy intensive and requires the use of chemicals, the environmental effects of recycling were observed to be lower than direct landfill (Huang et al. 2017). Faircloth et al. (2019) and Duflou et al. (2018) investigated three disposal options each. The former conducted an LCA on landfill, glass recycling and a dedicated recycling facility, whereas the latter included thermal delamination, glass recycling and mechanical cutting. Both studies concluded that upcycling via recycling was the best option for the environment.

The construction of a dedicated recycling plant in scenario 4 is disregarded. Taking that into account will result in higher environmental impacts than presented in this study. The transportation distance considered for each scenario is based on assumptions and information extracted from the pertinent literature. Therefore, in a real-time case, the distance from a collection point to the landfill or a recycling facility might be more or less, thereby altering the impact of transportation outlined in this research.

Moving further, it is also essential to highlight the limitations associated with the utilized input data. The electricity consumption data in scenario 3 is based on the estimation provided by Wambach et al. (2017) and, therefore, can vary (46 kWh/t – 84 kWh/t) depending on the throughput. Similarly, the recycling process accounted in scenario 4 is at a pilot scale, and therefore, the input and output data are also based on the estimations for a pilot scale which should be confirmed for an industrial-scale recycling plant. Furthermore, primary data is unavailable on phases not directly linked to the recycling process, such as transportation, incineration and disposal of hazardous and non-hazardous residues in a landfill. As a result, their impact is determined based on the inventory data available in the Ecoinvent database.

Daljit Singh et al. (2021) suggest that higher durability and more prolonged lasting solar PV panels and ancillary components are better for the environment than recycling. The common reasons for early failure of PVs identified by Chowdhury et al. (2020) include defects in manufacturing, erosion and degradation of a coating layer of EVA, which, if improved, can enhance the average lifetime of solar PVs and reduce the need of recycling.

The essence of the findings demands a circular approach to end-of-life solar PVs, especially in the context of process design. The suggested technique by Daljit Singh et al. (2021) for attaining circularity is standardization. Standardization will not only uncomplicate the design process of PVs but also standardize the disassembly and recycling procedures. Consequently, a circular end-of-life approach could eventually become an industry requirement.

In addition, the transportation phase, which has previously been mentioned to have a substantial negative impact on environmental sustainability (especially in climate change), needs to be addressed. Since improving the fuel efficiency and consequently reducing the environmental implications of conventional trucks and lorries is beyond the domain of end-of-life PV management, utilizing electric trucks can be a possibility (Mahmoudi et al. 2020). Electric trucks are superior to conventional trucks due to lower noise pollution, health hazards and adverse environmental impacts (Feng & Figliozzi 2012; Yang et al. 2018).

6.4 Economic

The sale benefit from recovered materials is crucial for the economic feasibility of recycling which is also consistent with the outcome of comparable studies (Lee et al. 2018; Faircloth et al. 2019; Liu et al. 2020). Innovation and improvement in recoverability and recycling will likely improve in the future, increasing the economic viability of recycling compared to landfilling the end-of-life PV waste. To discourage landfilling and promote circularity, tax policies and exemptions are critical. Spain’s current income tax rate of 25 percent (Talavera et al. 2019) should be reduced to attract investments in recycling facilities. Minimizing financing costs for loans is another method of increasing the economic viability of recycling.

The value of the recovered material can be optimized if it is employed as a high-value input in the original industry. For example, if a recovered material from PV waste is utilized for manufacturing new PV modules, it would reduce the dependence on virgin materials, thereby optimizing the material’s benefit (Latunussa et al. 2016; Liu et al. 2020). The financial value of recovered materials in scenario 4 is about 8.4 million euros, whereas the total cost of the same quantity of virgin materials would be considerably higher. This is because, unlike virgin materials, recovered materials do not have to bear the equipment cost and other associated expenses for material extraction. Markert et al. (2020) validate this conclusion by comparing the price of 1 m^2 recovered and virgin material. Recovered material costs 13.62 dollars per m^2, whereas virgin material costs 90 dollars per m^2.

On the other hand, recovered materials can also be utilized in diverse industries, such as manufacturing ceramic tiles, batteries, paint, cosmetics, mortar, and brick (Mahmoudi et al. 2020). Several studies in the literature have outlined recent applications of these materials, which corroborate the efficacy of recovered materials in various industries, especially in the future when recycling becomes more prevalent. Lin et al. (2015) stated that waste solar panel glass could be used to produce ceramic tiles after undergoing a series of mechanical and thermal treatment processes. In another research, Lin et al. (2012) emphasized the effects of substituting waste solar panel glass on the bricks industry for fabricating clay bricks. Not only utilized in other sectors, the recovered materials from end-of-life solar PV module can be utilized for producing lead-free solar PVs (Shin et al. 2017b).

6.5 Social

Social implications pertaining to the end-of-life solar PV management impact workers, consumers, local community, value-chain actors and society as a whole. Therefore, the social indicators, in this thesis's scope, embody distinct impact categories and stakeholder groups. Moreover, the incorporated social indicators are also directly aligned with the UN Sustainable Development Goals. 'Eco-industrial partnership' is relevant to SDG 9 (Industry, Innovation and Infrastructure), whereas 'Consumer awareness and public participation' is pertinent to SDG 12 (Responsible consumption and production) and 'Energy security' is associated with SDG 7 (Affordable and clean energy). 'Local job creation', 'Contribution of the technology to economic progress' and 'Health and safety of workers' are related to SDG 8 (Decent work and economic growth).

The two landfilling scenarios (scenarios 1 and 2) are socially less desirable than the two recycling scenarios (scenarios 3 and 4). The fact that landfill is the least socially sustainable end-of-life alternative is also corroborated by relevant end-of-life studies on waste plastics (Deshpande et al. 2020) and waste solar PV panels (Ganesan & Valderrama 2022). Ganesan & Valderrama (2022) also substantiate that full recycling or high-value recycling of end-of-life solar PV represents the highest degree of social sustainability.

6.6 MCDA

The weighting and ranking by utilizing multi-attribute value theory are subjective. From a technical standpoint, an objective examination of the effect of changes in weights on the model's output is essential (Deshpande et al. 2020). In such a case, attributing weights to criteria (sustainability dimensions) is opinion-based or data-based. The former approach, also employed in this thesis, utilizes subjective judgments from experts to ascertain weights for sustainability dimensions (Goulart Coelho et al. 2017).

To reinforce the outcomes of MCDA in this study, a comparison was drawn with other relevant studies (Deshpande et al. 2020; Ganesan & Valderrama 2022). Utilizing the weights assigned in the abovementioned studies, a sustainability score for each scenario was computed and compared with this study, as demonstrated in Figure 6.1.

'Case 1' signifies an economic weight of 0.34, an environmental weight of 0.42 and a social weight of 0.23. On the contrary, 'Case 2' represents an economic, environmental and social weight of 0.40, 0.35 and 0.25, respectively. It can be observed that the sustainability scores from this study can somewhat be correlated if the weights of other relevant studies are also utilized. Having said that, there are also some slight changes, such as the percentage-wise difference in scores for each scenario is higher for case 3 compared to the other two scenarios, especially for case 1 where a 62 percent difference between the scores of scenario 3 and 4 can be observed.

Similarly, Mastrocinque et al. (2020) outline four different cases which can cover the main range of priorities for each sustainability dimension. 'Case 1' represents an equal weighting approach for each dimension, whereas 'Case 2' characterizes a weight of 0.5 for social, 0.25 for both environmental and economic. In 'Case 3', double importance is given to the economic dimension, and in 'Case 4' double priority is assigned to the environment. The sustainability scores based on these four cases are compared with the score computed in this study, which is demonstrated in Figure 6.2. It is evident that the sustainability score for case 4 is significantly more than other cases.

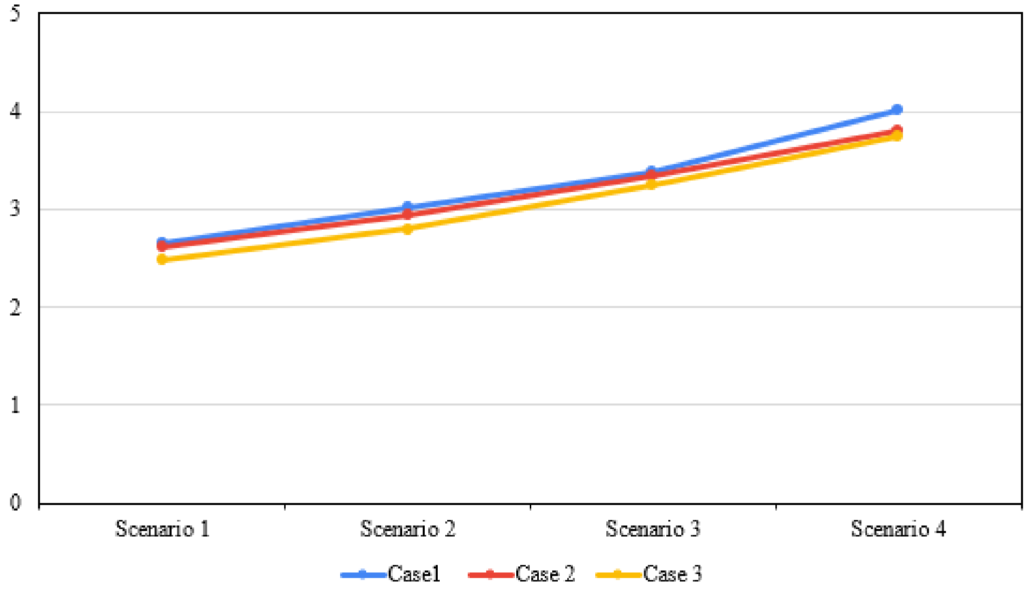

Figure 6.1. Sustainability score based on weights from other studies

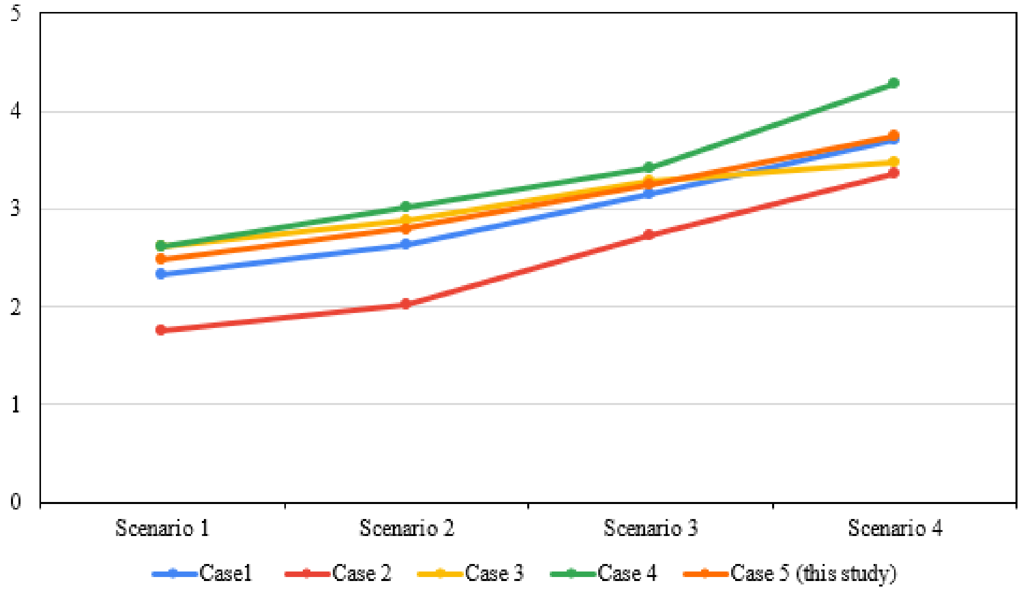

Figure 6.2. Sustainability score comparison of 5 different cases

6.7 Drivers, barriers and enablers

Culminating the application of a conceptual framework on Spain, an overview of the key drivers, barriers and enablers to sustainable end-of-life management of solar PV was seen as essential. The ‘take-make-consume-dispose’ approach that disregards a sustainable end-of-life strategy undermines solar PVs' status as a renewable energy source. With only a few developed countries beginning to recognize and establish pertinent policies for post-life management, it is vital to highlight the relevant drivers, barriers and enablers to promote the philosophy of circular economy in the solar PV sector.

The key drivers, barriers and enablers were shortlisted through an extensive literature review and are summarized in Table 6.1, Table 6.2 and Table 6.3. In addition to that, the corresponding stakeholders and target dimensions are also included.

Table 6.1. Drivers to sustainable end-of-life PV management

	Driver	*Dimension*	*Involved stakeholders*
D1	Reduced dependency on importing raw materials	Economic	Producer & Govt
D2	Job creation opportunities	Social	Producer, Recycler & Govt
D3	Reducing risks linked to human health	Social	Producer, Consumer & Recycler
D4	Minimizing energy payback time	Environmental	Producer & Recycler
D5	Lowering GHG emissions	Environmental	Producer, Consumer & Recycler

Table 6.2. Barriers to sustainable end-of-life PV management

	Barrier	*Dimension*	*Involved stakeholders*
B1	Lack of profitability to recycle	Economic	Producers & Recyclers
B2	Lack of financial incentives to collect & recycle	Economic	Producer, Installers & Govt
B3	Absence of consumer willingness to return end-of-life PV	Social	Consumers
B4	Coordination deficiency between producers and recyclers	Social	Producers & Recyclers
B5	Inadequate quantity of end-of-life PV	-	Producers, Consumers & Recyclers
B6	Energy intensive recycling	Environmental	Producers & Recyclers
B7	Emissions produced during recycling	Environmental	Producers & Recyclers

Table 6.3. Enablers to sustainable end-of-life PV management

	Enabler	*Dimension*	*Involved stakeholders*
E1	Economic incentives for an increase in collection & recycling	Economic	Govt
E2	Increasing cost of landfilling	Economic	Govt
E3	Facilitating stakeholder cooperation	Social	Producers, Consumers, Recyclers & Govts
E4	Developing industrial symbiosis	Social	Producers & Recyclers
E5	Encouraging extended producer responsibility	Economic	Govt

The questionnaire distributed to the experts included questions pertaining to the importance of each driver, barrier and enabler in their opinion. The four possible responses were: ‘high’, ‘moderate’, ‘low’ and ‘not applicable’. The aggregated responses for each driver, barrier and enabler are illustrated in Figure 6.3, Figure 6.4 and Figure 6.5.

It can be observed from Figure 6.3 that D5 was considered a ‘high’ impact driver by 77 percent of the experts, followed by D1 and D2 obtaining a ‘high’ impact driver status by 64 percent.

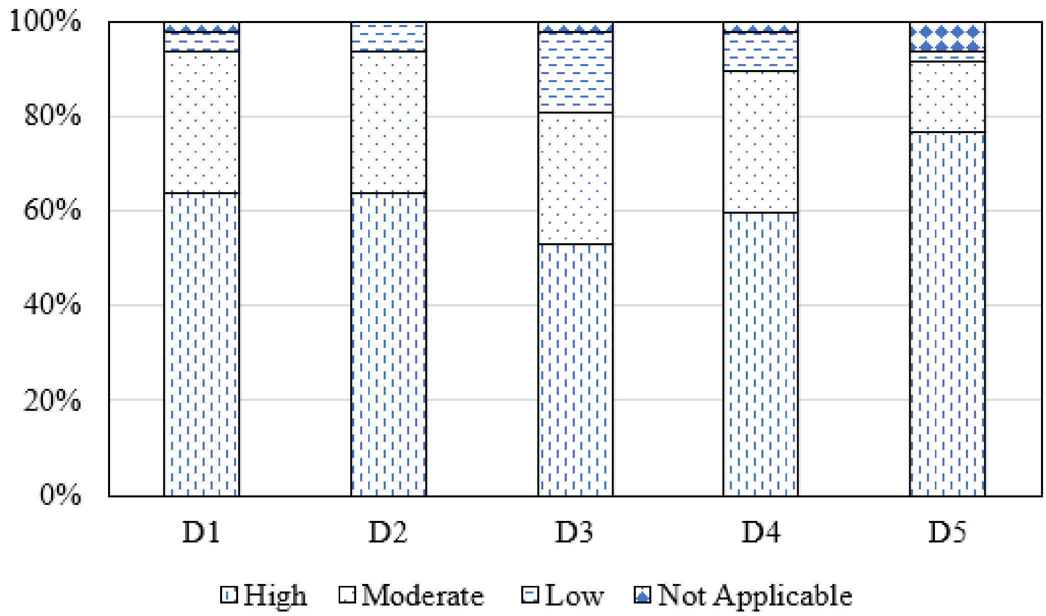

Figure 6.3. Expert responses to end-of-life PV drivers

Similarly, Figure 6.4 demonstrates that according to 57 percent of experts B2 is a ‘high’ impact barrier, whereas B1 and B4 a 55 percent ‘high’ impact barriers. B5 and B7 were considered as ‘high’ impact barriers by only 32 percent of the experts. E1 was regarded as a ‘high’ impact enabler by 77 percent of the experts, followed by 66 percent and 62 percent for E3 and E5.

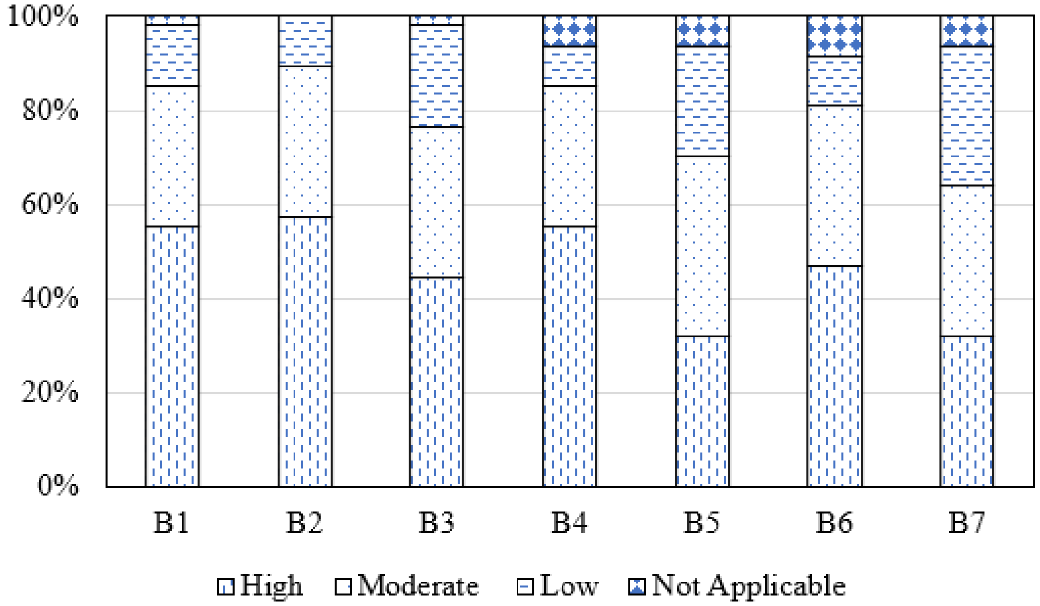

Figure 6.4. Expert responses to end-of-life PV barriers

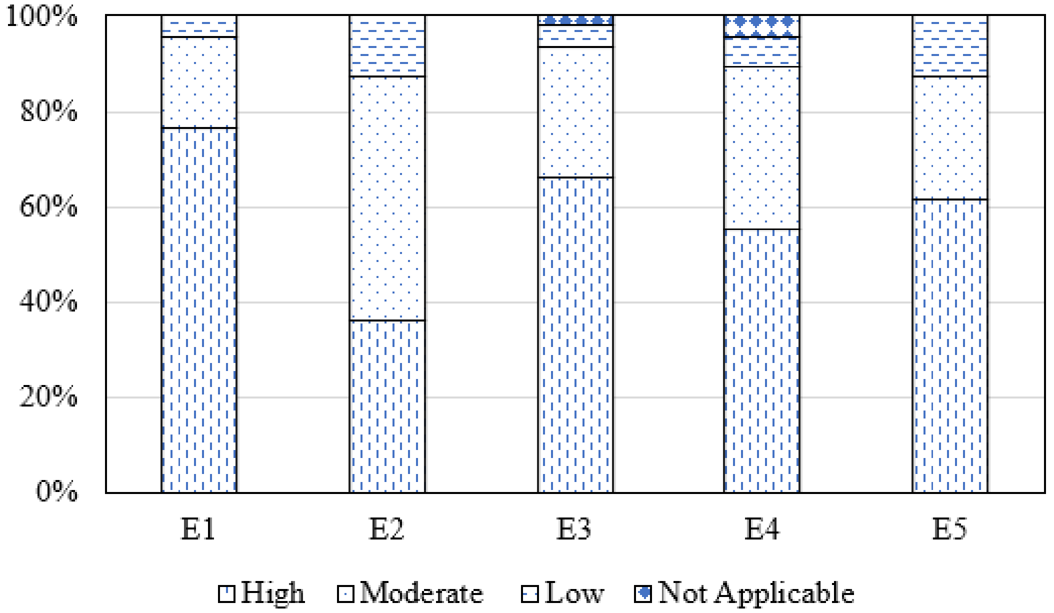

Figure 6.5. Expert responses to end-of-life PV enablers

Furthermore, the experts were also inquired about their opinion on which stakeholders were the most and least responsible for recycling end-of-life solar PV and regulations pertaining to end-of-life solar PV. The possible responses were: '1' (minimum responsibility), '2' and '3' (most responsibility). Figure 6.6 and Figure 6.7 demonstrate the final score against each stakeholder, where a higher score represents a higher responsibility, and a lower score characterizes a lower responsibility.

According to the experts, the manufacturers are the most responsible for recycling, followed by the installers. On the other hand, the users are the least responsible for recycling end-of-life solar PV. Regarding the pertinent regulations, the experts believe that the maximum responsibility lies on the government, followed by the manufacturers. On the contrary, the installers have the least responsibility regarding regulations.

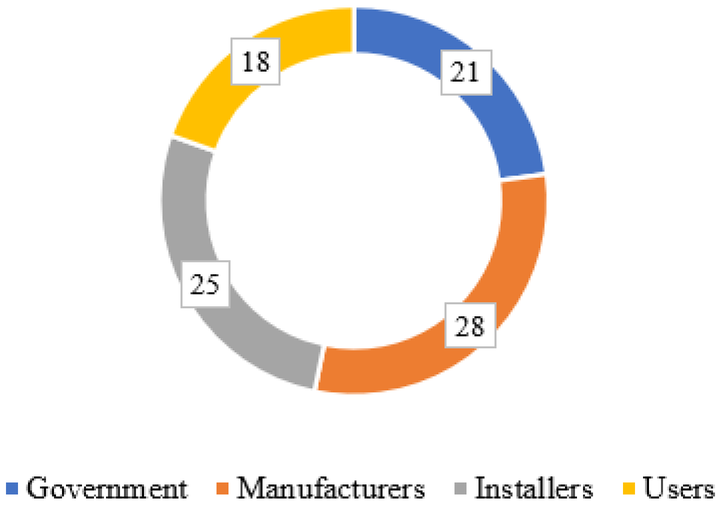

Figure 6.6. Expert responses to stakeholder responsibility for EoL recycling

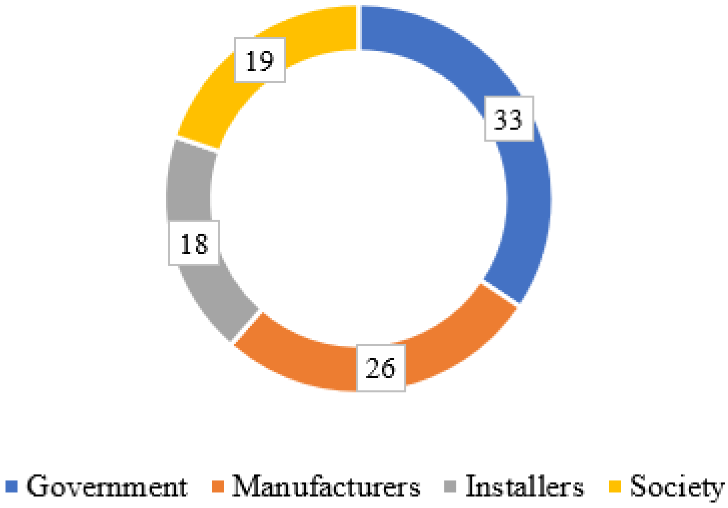

Figure 6.7. Expert responses to stakeholder responsibility for EoL regulations

CHAPTER 7

CONCLUSIONS

This thesis provides an integrated decision-making model to ascertain the sustainability extent of four end-of-life solar PV options. The devised framework is implemented as a case study on Spain to enhance the thesis granularity. The five main components of the model include: 1) forecasting of PV waste for two distinct installation periods and various waste projection scenarios, 2) life cycle assessment to ascertain the environmental implications, 3) cost-benefit analysis for determining the economic viability, 4) social assessment and 5) multi-criteria decision analysis for computing sustainability scores for each end-of-life option through expert responses.

Aggregating the expert responses, the assigned weights for each sustainability dimension (to determine the sustainability scores) are as follows: environmental (0.34), economic (0.37) and social (0.29). It was concluded that scenario 4 has the lowest economic sustainability under the current circumstances, whereas scenario 3 has the highest. On the contrary, scenario 4 is the most preferred option for environmental and social sustainability, with scenario 1 being the least desirable option from the lens of environmental and social sustainability. Taking into account the weights for economic, environmental and social sustainability, the overall sustainability score for each scenario is as follows: scenario 1 (2.48), scenario 2 (2.79), scenario 3 (3.24) and scenario 4 (3.76), where a higher score symbolizes higher sustainability.

Furthermore, emphasising drivers, barriers and enablers to sustainable end-of-life PV management is vital to encourage a paradigm shift from a linear to circular approach, where partial or full recycling is considered preferable alternatives. One of the most popular drivers among the experts is lowering greenhouse gas emissions generated during the solar PV production stage by enabling and promoting recycling. The scarcity of economic incentives for collection and recycling stages is seen as a significant barrier which, if resolved, can be the catalyst that can boost PV waste management and the recycling industry.

This thesis contributes to the contemporary literature via a conceptual construct that supports the triple bottom line. Incorporating expert responses to carry out a multi-criteria decision analysis and determining sustainability scores for each end-of-life option distinguishes this research from other studies. This thesis further contributes to the body of knowledge through the application of conceptual framework on Spain, with a viewpoint of providing better insights to policymakers and academicians for future studies. For this reason, the identification and validation of relevant drivers, barriers and enablers to sustainable end-of-life PV management is also included.

The thesis entails certain limitations regarding the systematic literature review, conceptual development and case study phases. The timeframe for the keyword search terms for the systematic literature review was from 2002 to 2021, which means publications in 2022 could not be accounted for. Moreover, the utilization of only two database aggregators means that the scope was restricted to a certain extent. The growth rates incorporated for the projection of PV waste in the second installation period were based on the author’s knowledge acquired through the literature research and relevant web pages, which means that the amount of PV waste, in reality, could vary.

Similarly, there are some limitations associated with the life cycle assessment as well. The recycling process in scenario 4 is still at a pilot scale, and therefore the input and output parameters are mere estimations which can vary on an industrial scale. Furthermore, the transportation distances are based on assumptions in the literature. The actual PV panel data (specifications and brand) is not utilized, and data from Ecoinvent was included, which can slightly alter the reliability of the findings. The costs and environmental impacts associated with the construction of a recycling facility are not accounted for, which, if included, can alter the outcomes to a significant degree.

Future research can incorporate other waste management alternatives like thermal and chemical delamination-based recycling, reuse and refurbishment. Also, this framework can be implemented on other types of solar PVs, such as thin-film modules and compared with the results of this research. In addition, the devised conceptual framework can be applied on a regional level within Spain and in other countries where the amount of solar PV waste could be substantial in future. More specific information regarding the chosen case study region should be obtained to yield even better and more reliable results, such as investment cost for land and building recycling plants and more precise information about the transportation distance.

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APPENDICES

A. Questionnaire # 1

1. Email *

2. 1. Full Name *

3. 2. Organisation *

4. 3. Country *

5. 4. How would you rate the importance of the following sustainability dimensions (on a scale of 1 to 5, with 1 being the least important and 5 being the most important), in terms of end-of-life PV? *

Check all that apply.

	1	2	3	4	5
Economic	☐	☐	☐	☐	☐
Environmental	☐	☐	☐	☐	☐
Social	☐	☐	☐	☐	☐

6. 5. Which of the following indicators are key to assessing the social impacts of end-of-life PV management? *

Mark only one oval per row.

	Not important	Less important	Important	Very important	Most important
Contribution of the technology to economic progress	⬭	⬭	⬭	⬭	⬭
Energy security	⬭	⬭	⬭	⬭	⬭
Health & safety of workers	⬭	⬭	⬭	⬭	⬭
Health & safety of local community/society	⬭	⬭	⬭	⬭	⬭
Local job creation	⬭	⬭	⬭	⬭	⬭
Consumer awareness and public participation	⬭	⬭	⬭	⬭	⬭

7. 6. In your opinion, impact of the following Drivers on EOL PV management? *

Mark only one oval per row.

	Low	Moderate	High	Not applicable
Reduced dependency of importing raw materials	⬭	⬭	⬭	⬭
Opportunities for job creation	⬭	⬭	⬭	⬭
Reducing human health risks	⬭	⬭	⬭	⬭
Reducing energy payback time	⬭	⬭	⬭	⬭
Lowering GHG emissions	⬭	⬭	⬭	⬭

8. 7. In your opinion, impact of the following Barriers on EOL PV management? *

Mark only one oval per row.

	Low	Moderate	High	Not applicable
Lack of profitability to recycle	⬭	⬭	⬭	⬭
Lack of economic incentives for collection & recycling	⬭	⬭	⬭	⬭
Absence of consumer willingness to return EOL products	⬭	⬭	⬭	⬭
Lack of coordination among producers and recyclers	⬭	⬭	⬭	⬭
Insufficient quantity of EOL PV	⬭	⬭	⬭	⬭
Energy intensive recycling	⬭	⬭	⬭	⬭
Emissions generated during recycling	⬭	⬭	⬭	⬭

9. 8. In your opinion, impact of the following Enablers on EOL PV management? *

Mark only one oval per row.

	Low	Moderate	High	Not applicable
Providing economic incentives for collection & recycling	⬭	⬭	⬭	⬭
Increasing landfill cost	⬭	⬭	⬭	⬭
Promoting cooperation among stakeholders	⬭	⬭	⬭	⬭
Developing industrial symbiosis network	⬭	⬭	⬭	⬭
Encouraging extended producer responsiblity	⬭	⬭	⬭	⬭

10. 9. Any further comments?

B. Questionnaire # 2

1. Email *

2. 1. Full Name *

3. 2. Organisation *

4. 3. Country *

5. 4. How would you rate the importance of the following sustainability dimensions (on a scale of 1 to 5, with 1 being the least important and 5 being the most important), in terms of end-of-life PV? *

Check all that apply.

	1	2	3	4	5
Economic	☐	☐	☐	☐	☐
Environmental	☐	☐	☐	☐	☐
Social	☐	☐	☐	☐	☐

6. 5. Which of the following indicators are key to assessing the environmental impacts of end-of-life PV management? *

Mark only one oval per row.

	Not important	Less important	Important	Very important	Most important
Climate change (CO2 emissions)	⬭	⬭	⬭	⬭	⬭
Ozone depletion	⬭	⬭	⬭	⬭	⬭
Fossil depletion	⬭	⬭	⬭	⬭	⬭
Acidification	⬭	⬭	⬭	⬭	⬭
Eutrophication	⬭	⬭	⬭	⬭	⬭
Human toxicity	⬭	⬭	⬭	⬭	⬭

7. 6. Which of the following indicators are key to assessing the economic impacts of end-of-life PV management? *

Mark only one oval per row.

	Not important	Less important	Important	Very important	Most important
Collection & Transportation Cost	⬭	⬭	⬭	⬭	⬭
Processing Cost (raw material, electricity)	⬭	⬭	⬭	⬭	⬭
Labour Cost	⬭	⬭	⬭	⬭	⬭
Disposal Cost (Hazardous and non hazardous waste)	⬭	⬭	⬭	⬭	⬭
Revenue Generation through Material or Energy Recovery	⬭	⬭	⬭	⬭	⬭

8. 7. Which of the following indicators are key to assessing the social impacts of end-of-life PV management? *

Mark only one oval per row.

	Not important	Less important	Important	Very important	Most important
Contribution of the technology to economic progress	⬭	⬭	⬭	⬭	⬭
Energy security	⬭	⬭	⬭	⬭	⬭
Health & safety of workers	⬭	⬭	⬭	⬭	⬭
Local job creation	⬭	⬭	⬭	⬭	⬭
Consumer awareness and public participation	⬭	⬭	⬭	⬭	⬭
Eco-industrial partnership	⬭	⬭	⬭	⬭	⬭

9. 8. In your opinion, which of the following stakeholders are most responsible for recycling end-of-life solar panels? (1 - minimum responsibility; 3 - most responsibility)

Mark only one oval per row.

	1	2	3
Government	⬭	⬭	⬭
Manufacturing companies	⬭	⬭	⬭
Installation companies	⬭	⬭	⬭
Users	⬭	⬭	⬭

10. 9. In your opinion, which of the following stakeholders are most responsible for regulations relevant to end-of-life solar panels? (1 - minimum responsibility; 3 - most responsibility)

Mark only one oval per row.

	1	2	3
Government	⬭	⬭	⬭
Manufacturing companies	⬭	⬭	⬭
Installation companies	⬭	⬭	⬭
Society	⬭	⬭	⬭

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Bilgisayar Mühendisliği / Computer Engineering ☐

Makina Mühendisliği / Mechanical Engineering ☐

YAZARIN / AUTHOR

Soyadı / Surname : Rizvi

Adı / Name : Syed Muhammad Ali Haider

Programı / Program : Sustainable Environment and Energy Systems

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Tez Danışmanı / Thesis Advisor Full Name: Prof. Dr. Murat Fahrioglu

Tez Danışmanı İmzası / Thesis Advisor Signature: ....

Eş Danışmanı / Co-Advisor Full Name: Asst. Prof. Dr Ali Berk Baştaş

Eş Danışmanı İmzası / Co-Advisor Signature: ....

Program Koordinatörü / Program Coordinator Full Name: Assoc. Prof. Dr. Ceren Ince Derogar

Program Koordinatörü İmzası / Program Coordinator Signature: ....