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Lean and Sustainable Framework for Solar Panel Recycling in Finland: A Systematic Literature Review

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ABSTRACT:

The popularity of solar power is increasing rapidly in Finland, although a solar panel has a useful life of about 25–30 years before it becomes waste. The recycling of solar panels is also applicable since Finland has set an objective of carbon neutrality by 2035. While the previous studies predominantly concentrated on the recycling technology and the circular economy concepts, operational challenges like long distances, waiting time, repeated handling, and bad sorting have been addressed less. These are problems that can get more complicated in Finland due to the long travel distances, cold winter weather, and the low population density. The overall research question of this thesis is, "What is the potential for using lean management principles in solar panel recycling systems in Finland for the sake of operational efficiency and sustainability?

Following the screening and selection process, 49 studies were included in the final review. Thematic synthesis analysis was used to analyse the findings, and they were summarised under the five core themes.

The thesis introduces Finnish cases of value stream mapping (VSM) for the redesign of collection routes between Oulu and Helsinki, 6S for workplace organisation and sorting in Tampere, and kaizen for continuous small improvements in Kuopio's collection hub. The study also suggests the use of measurable parameters like lead time, sorting accuracy, material recovery rate, and cost per ton for measuring the operational

KEYWORDS: Circular economy, Lean management, operational efficiency, PV recycling, Reverse logistics, Systematic Literature Review, Finland

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Abbreviations

BIPV	Building-Integrated Photovoltaics
CE	Circular Economy
CI	Continuous Improvement
EoL	End-of-Life
EU	European Union
IEA PVPS	International Energy Agency Photovoltaic Power System
JRC	Joint Research Centre
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RLS	Reverse Logistics System
SLR	Systematic Literature Review
VSM	Value Stream Mapping
WEEE	Waste Electrical and Electronic Equipment
6S	Sort, Set in Order, Shine, Standardize, Sustain, Safety

1. Introduction

1.1 Background to the study

The use of solar energy has been rapidly increasing in Finland today. Each year, more solar panels are being utilized. The solar power installed to the electricity grid in Finland was more than 1,200 MW by the end of 2024 (Energy Authority, 2024). That's a good thing, as many countries seek to increase their clean energy and reduce their pollution. However, there is another side to solar panels. They aren't permanent. Typically, solar panels have a lifetime of 25 to 30 years. From then on, they are garbage. It is also a goal in Finland to become carbon neutral by 2035 (Ministry of the Environment, 2021). This is why the proper handling of old solar panels is also important. However, PV waste, if not handled properly, also poses environmental issues in the future.

There also seems to be increased discussion about this issue in the EU. Around 21 to 35 million tons of PV waste could be in the EU countries by 2050, according to the Joint Research Centre (JRC) of the European Commission (Europa, 2025b). The European waste policies and recycling market are also linked to the Finnish recycling rules and producer responsibility as Finland is also part of EU system. This implies that PV waste issue cannot be neglected in the years to come in Finland. The majority of people believe solar PV is a completely clean technology due to the lack of fossil fuel combustion when generating electricity. However, there are numerous materials used to create solar panels, such as glass, aluminium, silicon, copper, silver and polymers (Wei et al., 2025a). The panels may be old or broken and end up in waste system. If there is no proper recycling and recovery process they remain there. Therefore, the thought should be given to the recycling in the future, when amount of waste will be considerable.

I'm not only a critic on recycling technology; from my side I think the problem is about recycling technology. While numerous studies address the technology and methods of treatment, as well as systems for material recovery, few address the entire recycling process step-by-step (Preet & Smith, 2024). There may be numerous trivial operation issues. For instance, the transport routes can be too long, panels can remain waiting for too long at collection sites, workers may process the same materials numerous times, etc. The process of sorting can also be lacking in strength at times. These are things that can make operations less efficient, and can even lead to higher operational cost (González-Reséndiz et al., 2018). I believe that lean management can contribute to this kind of situation, as lean, first and foremost, is about minimizing waste within the process. For example, using lean tools such as value stream mapping (VSM) and 5S, the problems occurring within the recycling waste flow can be identified, and the recycling process can be optimised in a more organised manner (El Hafiane et al., 2025). This is why this thesis investigates the possibility to make solar panel recycling more environmental and at the same time more efficient in terms of operations in Finland.

1.2 Research Gap, Research Question, and Objectives

1.2.1 Research gap

For this study, I searched the previous study using Scopus database to determine the research gap. The following keywords were combined with solar PV: recycling, circular economy, lean management, and Finland. Simple overview of how many papers were found for each of the combinations of keywords (see the table below).

Table 1. Number of study articles.

Keyword combination	Approximate number of hits
“solar PV” AND “recycling”	813
“circular economy” AND “PV recycling”	305
“lean management” AND “PV recycling”	10
“lean” AND “Finland” AND “recycling”	3

After I have searched and read through many papers, I found that most of the papers are concerned with the two aspects. Recycling Technology and material recovery from PV waste are the first areas. In the case of the separation of materials, such as glass, aluminium, silicon, and silver, from old solar panels, Wei et al. (2025) explain this, for instance, and Piedrahita et al. (2025) do the same. The second is the strategies of the circular economy for PV modules. The following studies talk about re-use, repair, second life usage, and policy and planning aspects of recycling systems.

However, there are certain literature gaps. There are hardly any studies on the detailed discussion of the operating side of the PV recycling system. Some papers mention problems such as transport planning, waiting time, sorting quality, network of collection, storage layout and coordination, but primarily these are side issues. They are not studied in the correct way, using an operational framework. Iakovou et al. (2024) and Franz and Piringer (2020) provide examples that long distances and a lack of organised recycling facilities are significant challenges for PV end-of-life systems. But these studies do not use lean management tools for improving those operational problems in a systematic way. Other research, such as Marinna et al. (2025) and the IEA PVPS report (Aspects, 2026) are available on second-life use and reuse decision making, but do not provide a lot of information regarding operational efficiency in process flow on a day-to-day basis.

One more thing I noticed from my own reading was. Mostly, when many authors refer to “efficiency” or “better performance,” they talk in generalities. They tend to say that one system is sustainable or efficient compared to another system, but they don't clearly distinguish an indicator of how the system works, such as transport distance, lead time, waiting time, number of handling steps, or sorting defect rate (Luu et al., 2025; Sasso et al., 2025). Hence, it is hard to gain a clear picture of what operational improvement is in a real situation. I also observed that there is a lack of studies on the link between the circular economy and lean management, in particular, in the context of solar panel recycling in Finland. Policy or system level (Lindahl, 2024) is where the circular economy is often addressed. The application of lean management is more popular in manufacturing systems and in general logistics systems, but not in the PV recycling business. Although some recent papers explain how lean can help reach circular economy objectives by minimizing waste within the process, they still fail to describe the whole working process for recycling solar panels in a specific national context, such as Finland (El Hafiane et al., 2025; Teixeira et al., 2025a).

From these observations, the following research gaps can be explained about this thesis:

- No operational framework has been created to merge lean management and the circular economy, particularly for the PV recycling situation in Finland.
- There are no clear-cut definitions and classifications of measurable indicators of operational efficiency and sustainability performance in PV end-of-life systems as present in the literature.

This gap is primarily a knowledge gap, and in part, a conceptual gap. It is related to the possibility of linking circular economy, lean management, and PV recycling to one possible framework for a specific country case. This thesis tries to fill this gap by developing a conceptual framework that links lean management practices, operational efficiency, and sustainability performance in solar panel recycling systems in Finland using a systematic literature review and synthesis of existing studies.

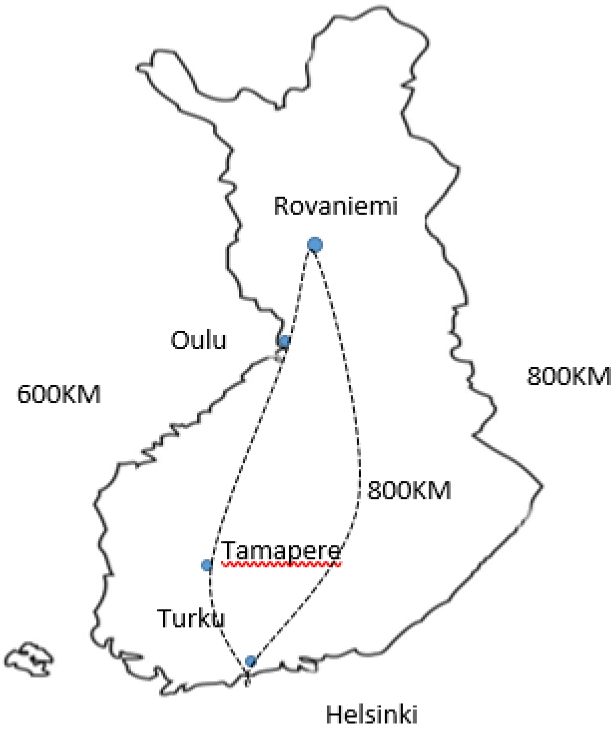

Figure 1. Map of Finland with major cities and transport distances

1.2.2 Research question

Based on the research gap explained above, the main research question of this thesis is: How can lean management principles be used to improve operational efficiency and sustainability performance in solar panel recycling systems in Finland?

The primary focus of this research question is the connection between lean management practices, PV recycling operations, and sustainability outcomes in the context of Finland. It also examines the geographical situation and policy framework in Finland concerning the recycling of solar panels.

1.2.3 Research objectives

To answer the research question, this thesis has four main objectives.

1. To review the current problems of PV end-of-life.

This objective includes studying technical, logistics, organisational, and policy-related problems which can affect PV waste flow and recycling results.

2. Assess options for solar panel recycling within a circular economy.

In this part, re-use, repair, second-life use, recycling, and other circular pathways referred to in the previous literature concerning PV systems are summarized.

3. To understand the role of lean management in enhancing operational efficiency.
This objective is centred on the understanding of lean management principles and tools that can be used to minimize the waste and increase the efficiency of PV end-of-life systems.

4. To create a conceptual framework that combines the concepts of lean management and the circular economy.
The framework is based on a particular focus on Finland context. It links lean practices, operational efficiency, and sustainability performance of solar panel recycling systems.

1.3 Definitions and Scope of the Study

1.3.1 Definitions of key terms

Here, some important concepts, which are utilized in this thesis, are explained. First, various definitions from the literature are discussed, and then, I provide an explanation of the use of these terms within this study.

Circular economy
The main concerns regarding the circular economy in the PV sector are the use of products and materials over a longer time, the prevention of waste, and the loss of resources. According to Lindahl (2024), designing the system in such a way that materials remain in use as long as possible. The other definition for circular economy is the one from Europa (2024b), which views it as a system where products and materials are recycled, remanufactured, refurbished, repaired, and reused, rather than being discarded at the end-of-life stage.

This thesis is based on the definition of circular economy as primarily a strategic approach to the PV recycling system. It involves the reusability of solar panels through reuse, repair, second-life uses, and high-quality recycling for as long as possible. A range of policy instruments is also crucial for the system, such as the Ecodesign for Sustainable Products Regulation and Digital Product Passports (Europa, 2024b; Europa, 2026). The thesis builds on the idea of the operational conditions put forward by Lindahl (2024), but with a special focus on the context of PV recycling in Finland.

Lean management

Lean management is typically described as a technique to detect and eliminate waste within the process and to enhance the process flow and customer value (González-Reséndiz et al., 2018). The other explanation states that lean is a systematic method for reducing non-value activities, the efficient use of resources, and for helping the environment to be well performed (El Hafiane et al., 2025).

In this thesis, lean management is applied primarily from an operational perspective. It emphasizes minimizing the waste of the process within the PV end-of-life system. These include unnecessary transport, repeated handling, long wait times, poor layout, contamination, and sorting errors, etc. Lean tools such as value stream mapping (VSM) and 5S are essential tools that serve to structure the work process, enhance flow and facilitate continuous improvement (CI) activities (Teixeira et al., 2025a).

Operational efficiency

Operational efficiency is the efficiency of the process in the use of resources such as time, money, labour, and materials to produce output (Ghaithan et al., 2023). Others consider it as the relationship between input and output within the system, which can be measured in various ways depending on the type of operation (Prashar & Chaudhuri, 2025). Operational efficiency in PV recycling from the PV recycling point of view in this thesis refers to the reduction of wasteful time, handling, and transport distance in solar panels moving from collection to transport, sorting, dismantling, and material recovery without compromising solar panel recycling output. Some indicators might be distance travelled per tonne, number of handling steps, lead time from decommissioning to recycling, and percentage of correctly sorted panels for re-use or recycling.

The distance of the transport is most likely one of the most significant factors in operation in Finland, as collection locations and recycling facilities may be far away from each other. This results in higher transportation costs and emissions (Franz & Piringer, 2020). Winter seasons can also cause delays, increased fuel consumption, and issues with fuel handling. Therefore, optimization of the transport routes and stable winter operations are crucial to enhancing the recycling efficiency of PV in Finland.

PV recycling

PV recycling is the process of reclaiming materials from discarded solar panels, as explained by many studies. Typically, these investigations tend to be more technical, such as delamination and separation of glass, metals, and semiconductor materials (Wei et al., 2025). A more comprehensive definition also encompasses collection, dismantling, separation, and recovery phases that are associated with recycling facilities (Preet & Smith, 2024).

In this thesis, the term 'broader definition' refers to a larger definition. PV recycling involves the entire process from removal of the solar panel from service to material recovery in the recycling facility. It also involves collecting, transporting, storing, testing, sorting, dismantling, and separating materials, as well as final recycling technology.

Reverse logistics

Reverse logistics is the flow of products or materials from the point of final use back to the place where they can be reused, repaired, recycled, or disposed of appropriately. According to PV literature, reverse logistics has been defined as collection systems, transport routes, and types of pre-processing of the panels before they are delivered to the PV recycling centres (Iakovou et al., 2024). In addition, some studies address reverse logistics systems (RLS), which also involve network design, environmental performance, and operational cost (Zhou & Li, 2025).

Reverse logistics in this thesis refers to the physical and organisational flow of solar panels following the stage of their decommissioning. This encompasses collection from local areas, consolidation, and long-distance transport and movement toward a reuse and/or recycling facility. One such aspect is reverse logistics, which is crucial for minimizing transport waste, waiting time, unnecessary movement, and defects in the process of lean management.

Finland (in this thesis context)

In this thesis, the country location is not the only one discussed when referring to Finland. Finland is also a very specific operational context, where the end-of-life management of PV is affected by various factors. Finland's population is estimated to be about 5.6 million, and the majority of the population is located in the southern part of Finland. The inter-city distances are great. For instance, the winter season is cold and dark, and snow and ice may slow down or make transportation more difficult (Franz & Piringer, 2020).

The waste policies of Finland are linked to EU policies and directives, such as the WEEE directive (Europa, 2025b) and the producer responsibility system. Finland also has a carbon neutrality target by 2035, and the capacity to generate solar power has been growing continuously over the years (Energy Authority, 2024; Ym, 2026). This thesis aims to concentrate on the geographical, logistical, and policy challenges for Finland as they influence the development of a lean and circular PV recycling system in a practical situation.

1.3.2 Scope of the study

The main emphasis of this thesis is set on the end-of-life management and recycling of solar panels in Finland. The study explores the subject from the combination of both circular economy and lean management approaches. Focus on the operational process and system organisation is given. This study does not focus on detailed chemical and/or thermal reaction mechanisms.

The different stages of crystalline silicon PV panels after the EoL stage are included in this study. It covers the process starting from decommissioning until material recovery. A variety of operational activities are also covered, including collection, transport, sorting, dismantling, temporary storage, and pre-processing. This paper also covers the discussion on circular economy strategies related to the PV waste systems. These encompass re-use, repair, second-life use, and recycling of solar panels. Lean management principles and tools are also included in this thesis as they can be used to analyse and improve the process efficiency of the operations.

Finland context is also an important aspect of this study. Finnish geography is included as it influences the PV recycling operations in practice, as well as the recycling market and policy system. There are certain things that are not covered by this thesis. This does not include the production of new solar panels. The discussion does not go into great detail on the energy generation and use phase of PV systems, except where it is relevant to the understanding of when they reach the end of their life. This Thesis does not provide technical detail on detailed chemical, thermal, and mechanical recycling technologies as it focuses more on the operational and management aspects of recycling systems. Other countries are briefly mentioned only when they are being compared or explained. This study does not include other types of waste, such as other PV-related components.

Operational and sustainability indicators are also covered in this thesis. Examples include transport lead time, transport distance, cost per tonne of PV waste, material recovery rate, waiting time at PV waste collection, and sorting accuracy. When talking about process improvement, these indicators are related to lean tools such as value stream mapping (VSM), 5S, and Kaizen. These indicators were chosen due to being practical and more realistic to measure in the context of Finnish PV recycling. Operational-level logistics and handling data can generally be made available for these indicators to gain a clearer view of the process efficiency. They also have an impact on environmental performance as well as operational cost. There are other reasons for using these indicators as well; they can be used to link lean management tools to measurable improvements within actual recycling operations.

1.3.3 Finland context

Finland is a country with approximately 5.6 million inhabitants, with a majority concentrated in the southern part of the country. The area of the country is vast; distances are great between places. In addition, there are also numerous rural areas that are sparsely populated. For example, the distance from Helsinki to Oulu is around 600 km and from Helsinki to Rovaniemi is around 800 km (Franz & Piringer, 2020). During winter, the weather in northern Finland may be very cold. Occasionally, temperatures fall below -20°C for extended periods of time. Road transport is affected by snow, ice, and strong winter storms, and it may even be completely blocked for a short time (Franz & Piringer, 2020). This will then cause more expenses and time in moving PV waste from one place to another than in countries with shorter distances and favourable weather conditions.

Finland adheres to the EU waste laws and regulations. This consists of the WEEE directive for electronic and electrical waste. In addition, there are examples of producer responsibility systems in use in Finland for numerous products (Europa, 2024b; Europa, 2025b). Still, there is as yet no such large special PV recycling centre in Finland. Recycling activities also occur via smaller systems, and some panels can be exported for recycling to other EU countries. This can lead to increased transport distances and may raise the recycling cost, particularly for panels from long distances. The highly dynamic solar energy market in Finland is still smaller than some of the largest EU countries, but the development is going fast. In 2024, Finland already had over 1200 MW of PV power installed, in 2024. (Energy Authority, 2024). The majority of these panels can be considered end-of-life waste in the 2040s and 2050s. The estimated amount of PV waste in Europe is estimated to be around 21-35 million tonnes by 2050 (Europa, 2025b). Based on the share of PV waste from the EU population, the amount of PV waste in Finland could also be hundreds of thousands of tonnes in the future years. It's just a simple estimate by the writer and not an official figure, but it does indicate that the amount of waste produced in the future will be significantly larger.

For this reason, Finland has a few months to work on the planning of the PV recycling system. However, when planning and preparation are too far into the future, they can cause inefficiencies in the future recycling system. Excessive transport, delays in processing, increased environmental impact, and loss of quality of the materials during handling and storage.

1.4 Structure of the thesis

This thesis has five chapters. The findings and discussion have been integrated into one chapter; this helps in avoiding repetition of the same points and makes the discussion easier.

Chapter 1 – Introduction

This chapter describes the background of the study, research gap, research question, and research objectives. It also presents important concepts, the scope of the study, and the Finnish context of PV recycling.

Chapter 2 – Literature review

In this chapter, the previous studies related to PV waste management, circular economy, and lean management are discussed. It defines the interconnections between these topics and their gaps in research. A conceptual framework of this thesis is also introduced at the end of the chapter.

Chapter 3 – Methodology

The study was conducted by applying the method of systematic literature review and is described in this chapter. It encompasses research design, search strategy, screening process, inclusion/exclusion criteria and quality assessment and data synthesis. It also elucidates the coding process and the development of the final themes from selected studies.

Chapter 4 – Findings and Discussion

The results of the literature review are presented as follows: there are five main themes presented in this chapter. Firstly, the results obtained in the literature are explained, and then the discussion is linked to the context of Finland. The chapter also provides examples of how lean management tools can be applied in the PV recycling operations in Finland. Findings are linked with the conceptual framework and the proposed indicators.

Chapter 5 – Conclusion

This is the last chapter of the thesis. It provides a summary of the key findings and discusses the methodology used to reach the research goals. It also discusses the contribution of the study, practical implications, policy implications, limitations, and suggestions for future research related to lean and circular approaches in PV recycling systems. The research problem and research gap were explained in this chapter, as well as the research objectives, research definitions, and research scope. Literature related to PV waste and circular economy, and lean management is discussed in more detail in the next chapter.

2. Literature Review

2.1 Introduction

The literature discussed in this thesis is reviewed in this chapter. The main focus is on three topics that are interconnected. These are PV end-of-life management, circular economy, and lean management. The aim of this chapter is to describe these subjects individually but also illustrate the link between these subjects and the significance of this link for solar panel recycling in Finland (Teixeira et al., 2025a).

The first part of this chapter, which is Section 2.2, discusses PV waste and recycling systems. This involves anticipated growth in PV waste, materials within the solar panels, and various technical and logistics issues raised in past research. The concept of the circular economy is explained in section 2.3, and how it affects the PV end-of-life management. The circular economy is a more relevant approach than the “use and throw away” model, since it has given a greater value to re-use, repair, second-life use, and recycling. In Section 2.4, lean management is discussed, and lean concepts and tools can potentially be used to enhance PV recycling and end-of-life operations. These three sections are merged in the final section (Section 2.5), and the conceptual framework used in this thesis is presented. Due to this structure, Chapter 2 follows the general discussion of PV waste to a more analytical discussion of the connections between the circular economy and lean management in the context of PV recycling in Finland.

2.2 Solar panel recycling and PV end-of-life management

2.2.1 Growth of PV waste and the need for system planning

Numerous studies demonstrate that PV waste is emerging as an important issue, and far beyond being a small environmental topic. It is noteworthy that earlier reports from IEA PVPS already indicated that the amount of PV waste at the end of life will grow significantly with the age of PV installed systems (Pvps, 2012). Around 6-13 million tonnes of PV waste is estimated to result from the EU-27 by 2040 and 21-35 million tonnes by 2050, according to more recent estimates from the Joint Research Centre of the European Commission (Europa, 2025b). Clearly, these numbers indicate PV waste management is a major issue within the renewable energy sector.

Meanwhile, a number of these estimates are just at the EU level. They are not always able to provide a good exchange of PV waste between countries and regions (Nieto Morone et al., 2025). This is a limitation due to the need for recycling and collection systems to be better planned. Knowledge of only the total amount of waste is not sufficient. Information is also needed by countries on where the waste will be, and when it might occur. The same can be observed on the country level. A recent EU-oriented study based on National Energy and Climate Plans revealed that an increase in the amount of PV waste is expected in many EU countries. While in Italy and Germany, PV end-of-life waste is on the rise, the situation is the same in Finland, albeit to a lesser extent (Nieto Morone et al., 2025). This study was helpful for the EU-level projections to be used in Finnish planning, as Finland is in the wider European PV waste system and regulations (Europa, 2025b). However, the study focuses on Finland merely as a part of a wider comparison and does not delve into operational questions in depth. For instance, it doesn't mention the number of collection points, transport routes, or operational distance issues.

Therefore, it is not only the amount of PV waste but the main issue, as presented in the literature, is the quantity of PV waste in the future. Another is that countries need systems in place to collect waste: to log waste, to test waste, and to recycle/reuse waste before there is too much (Pvps, 2012; Europa, 2025b). Early planning is significant for Finland, as the power capacity of solar power is growing and the solar panels of today can become waste in the coming decades (Energy Authority, 2024). Up to now, a number of studies have provided only generic predictions of the future volume of PV waste. There are still fewer studies giving practical operational designs, especially for Nordic countries or sparsely populated areas. Due to this, further applied research on related subjects concerning the Finnish context is still required, and this thesis aims to contribute in this respect.

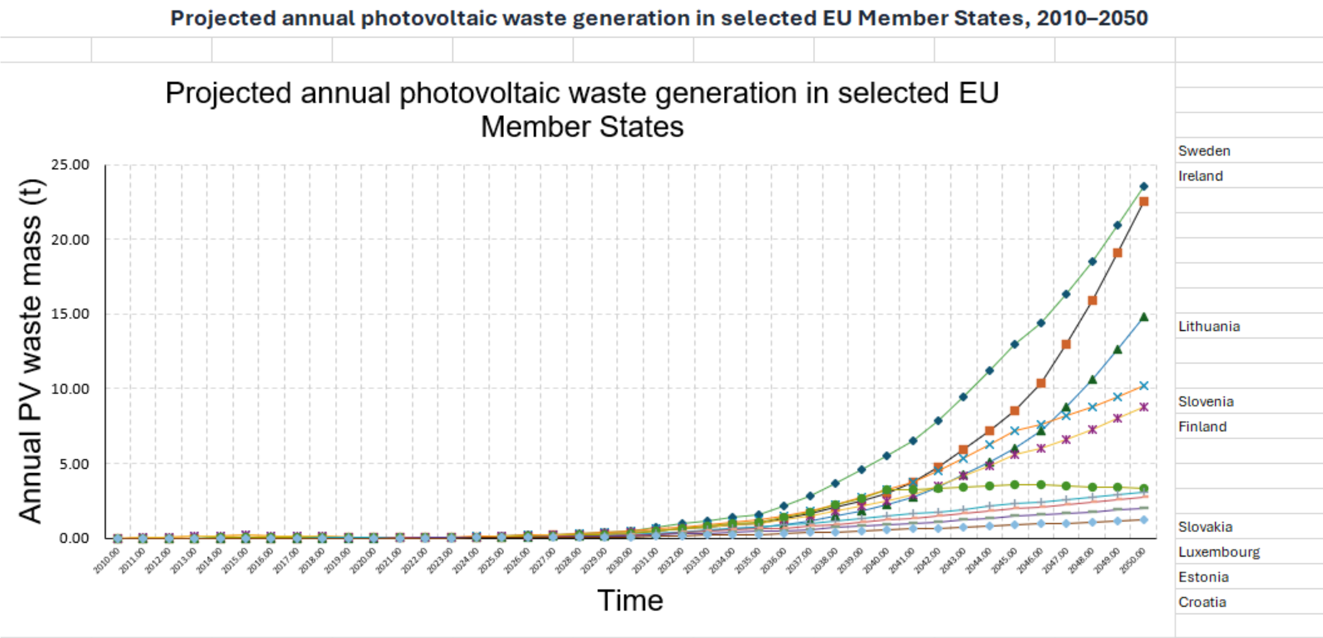

Figure 2. Projected annual photovoltaic waste generation in selected EU Member States, 2010–2050 (MDPI)

2.2.2 Composition of PV modules and recovery challenges

The recycling process is dependent on the materials contained within solar panels. The solar panels available today are mainly the crystalline silicon modules. The panels are made with a great quantity of glass and aluminium. They also have smaller amounts of materials like silicon, copper, and silver, which are more valuable economically (Wei et al., 2025). The science of crystalline silicon recycling backs this up, with the management of valuable materials still complex and costly. Recycling of glass and aluminium is easier, and the recovery of silver and silicon of high purity is difficult (Wei et al., 2025).

This difference matters when it comes to talking about recycling performance. Although a large percentage of total weight may be recovered in a recycling system, high material value may not necessarily be recovered. The value of glass and aluminium is lower than that of silver and pure silicon (Wei et al., 2025), which are heavier materials. For this reason, full weight recovery should be the only measure used to give an incomplete picture. Another problem is related to the objectives of the circular economy. If the recycling system is mainly focused on low-value materials, useful materials are lost or degraded, then the objectives of the circular economy are not met. Reducing the amount of waste is not the only aspect of the circular economy. It also relates to the ability to maintain the value of material for a longer period of time (Luu et al., 2025; Lindahl, 2024).

A lot of technology-based research continues to report the success of recycling primarily in terms of mass recovery. As a result, the recycling results may sometimes appear to be better than reality. It's not just about losing weight; it's about losing material value. Some open-access papers that discuss PV waste management also provide details on recoverable materials such as glass, aluminium, copper, and silicon from old solar panels. However, the ultimate recovery depends upon a variety of factors such as process design, recycling cost, and technology selection (Piedrahita et al., 2025). Due to this, recycling performance is not the only indicator that can be used to measure the possibility of solar panels reaching landfills. Furthermore, it is important to consider the quantity of useful material retained for future use (Wei et al., 2025; Piedrahita et al., 2025).

However, from the literature, I also noticed that there are not so many studies that discuss measurable operational indicators associated with these recovery problems. An example of this is that less research has been conducted to measure the economic value of one module or the amount of silver recovered from one tonne of PV waste (Luu et al., 2025). As a result, comparisons of recycling systems in a practical manner are not easy. Numerous operational issues regarding the handling of PV modules and recycling are also mentioned in the literature. These are the challenging material separation, high recovery cost for silver and silicon, weak reverse logistics, long transport distance and lack of proper testing systems for reuse applications (Wei et al., 2025; Piedrahita et al., 2025; Iakovou et al., 2024; Franz & Piringer, 2020; Marinna et al., 2025).

These are typically addressed as stand-alone issues in most studies. Typically, they will not examine the linkages between these issues within a single process of operation. Here, lean management can be helpful, as it can lead to a more systematic approach in identifying waste activities and problems with processes.

2.2.3 From treatment technology to reverse logistics

Previous investigations focused primarily on technology applied to treatment within recycling facilities. The main focus of the research was disassembly, delamination, and recovery of materials from solar panels. However, more recent studies are beginning to address broader systems as well. These studies elucidate that the performance of recycling is not solely based on the treatment technology. This also relies on the collection systems, transportation, sorting, network planning, and policy conditions for panels to reach the recycling facility (Preet & Smith, 2024; Iakovou et al., 2024).

PV recycling process has been described as a complete process by Preet and Smith (2024), which involves the disassembly and delamination of the PV and further recovery of valuable materials. They also state in their study that recycling technology is not the sole solution. In addition to technology, operational factors, social conditions, and cost effectiveness are also crucial (Preet & Smith, 2024). This is consistent with the idea that if end-of-life management for PV is to be thought of as a bigger system than just recycling plant activity. However, although Preet and Smith (2024) mention system-level thinking, they don't detail how the logistics side can be improved in practice. Their study describes the issues that occur in the system, but doesn't give detailed solutions to reduce inefficiency within the collection and transport process.

The same thoughts are reflected in several studies of reverse logistics. As Iakovou et al. (2024) explain, the lack of organised and optimised PV recycling facilities is one of the greatest challenges in the management of PV end-of-life. In addition to recycling technology, their study indicates that the performance of recycling relies on the transport routes, the location of the recycling facilities, the routing system, network planning and policy support (Iakovou et al., 2024). However, they do not deeply delve into any day-to-day issues such as waiting time, repeated handling or unnecessary movement of items during process flow, etc., but mostly discuss at the level of network design.

There are also some network optimisation studies that discuss these issues. Zhou & Li (2025) suggest that environmental and economic performance need to be taken into account for the reverse logistics systems of retired BIPVs. They believe that recycling and decommissioning routes should be designed with multiple objectives and take care of their study (Zhou & Li, 2025). However, most of these models are theoretical and have not been tested in the Nordic and Finnish environment, where the distances for transporting them are very long and the winter weather may cause extra operational challenges.

Table 2 below shows some important studies related with PV end-of-life systems and their limitations.

Table 2. Selected studies on PV end-of-life systems and their limitations.

Author(s)	**Focus area**	**Key finding**	**Limitation/gap noted**
(Iakovou et al., 2024)	Reverse logistics	Poorly optimized facilities are the major challenge in the reverse supply chain.	Lean tools not used to analyse process wastes.
(Preet & Smith, 2024)	Recycling technology	Transport, policy, and system conditions have to be considered in addition to technology	No detailed operational framework for the logistics process.
(Wei et al., 2025a)	Network optimization	Recycling routes need to take into account environmental and economic performance.	Not tested in Finland or Nordic conditions

As per the above comparison, there are some studies that have already recognized the issues existing in the PV recycling system. However, the majority do not progress beyond creating a practical working plan for implementing recycling in the day-to-day activities. In particular, these studies do not consider lean management as a structured approach to identify and minimize process wastes in the reverse logistics chain. This is one of the salient gaps filled in this thesis.

In summary, these studies indicate that the end-of-life management for PV can be considered as a complex system of technology, logistics, economy, and policy. This opens up an important space for lean management, since lean is primarily geared towards system-level improvement, waste reduction, and process flow (González-Reséndiz et al., 2018; El Hafiane et al., 2025).

2.2.4 Why these findings matter for Finland

These issues are of great significance for Finland at a system level. Finland has some special circumstances that may complicate the PV recycling process, as explained in earlier studies. Some of these are long distances for transportation, the scattered solar installations, and the weather conditions, or the still evolving solar market (Franz & Piringer, 2020; Nieto Morone et al., 2025). Due to these factors, the reverse logistics activities in Finland can be more costly and less efficient than in countries where cities and recycling plants are nearer.

Currently, the PV market in Finland is smaller than in the large PV countries in the EU (Energy Authority, 2024; Nieto Morone et al., 2025). However, the capacities of solar power plants have been growing each year, and research has indicated that the amount of PV waste will also rise significantly in the coming decades (Europa, 2025b; Pvps, 2012). PV waste can initially remain small and scattered at various sites. As a result, there is a tendency for wasteful management of waste in an unorganized manner. However, later there can be operational issues, such as sub-optimal transport routes, extended storage duration, repeated handling and even compromises of material quality before panels are directed towards recycling facilities (Iakovou et al., 2024; Franz & Piringer, 2020). Although these risks are mentioned in many studies, they do not generally give a vivid picture of how the practical recycling system in Finland should be organised to prevent the problems. Shows the need for improved operational tools and planning methods.

One solar panel taken off the farm in Lapland can spend many months in the collection area, as the collection is not frequent. Then, the panel can be conveyed for up to 600 kilometres to the sorting centre in Oulu and from there on a long journey towards the recycling centre close to Helsinki. This process can involve the same panel being loaded and unloaded numerous times. It can also be stored at various sites for several days or weeks. The panel can also be damaged during transport and storage due to the cold temperature, freezing, and thawing (Franz & Piringer, 2020). These are examples of transport waste, waiting waste, and defect risk, from a lean management point of view. All these decreases in operational efficiency can also drop the quality of recovered materials.

This makes Finland a key case to link PV recycling research to the concepts of lean management. PV recycling literature references the rise in waste production and dependence of the waste in the PV systems, and lean management offers tools to analyse the flow and reduce waste in the system (Teixeira et al., 2025a; El Hafiane et al., 2025). The concepts of circular economy and lean management are elaborated in more detail in subsequent sections and then merged in one concept in a later section in the context of the Finnish PV recycling system.

2.3 Circular economy in PV recycling

2.3.1 Circular economy as the strategic direction

Circular economy transforms the attitude towards PV end-of-life management. A normal linear system is the production of a solar panel, its use in electricity generation, and subsequent discarding as waste. In the circular economy, however, the solar panel is considered as waste not only at the end of its use. It is regarded as a product with materials and functions which are expected to remain useful within the economy for as long as possible (Lindahl, 2024). Due to this, reuse, repair, refurbishment, second-life use and high-quality recycling becomes important instead of trying to avoid landfill (Europa, 2024b; Europa, 2026).

This direction is already evident in the EU level in new policies and regulations. This includes the development of Ecodesign for Sustainable Products Regulation (Europa, 2024b) and Digital Product Passports (Europa, 2026). The policies aim to increase the durability, repair and reusability of products. They also seek to make product information more transparent by providing information on materials, origin, environmental impacts and end-of-life options. For solar PV systems, it is important to start considering end-of-life only when the solar panel is waste. It should already start during design and installation stage. Addressing better tracking of components, materials and information on performance is also a key element in this approach (Europa, 2024b; Europa, 2026).

However, from literature I noticed that there is not much discussion going beyond policy and strategy within the circular economy. The concepts of keeping value in the system or closing loops are discussed in studies, but there is not a clear message on how to change the operational work in every day. For PV systems in particular countries, there is little information on the collection activities, testing systems, sorting process and transport operations. This leaves a gap between policy ideas and the operational system design, however. This thesis attempts to shed light on this gap in the context of PV recycling in Finland.

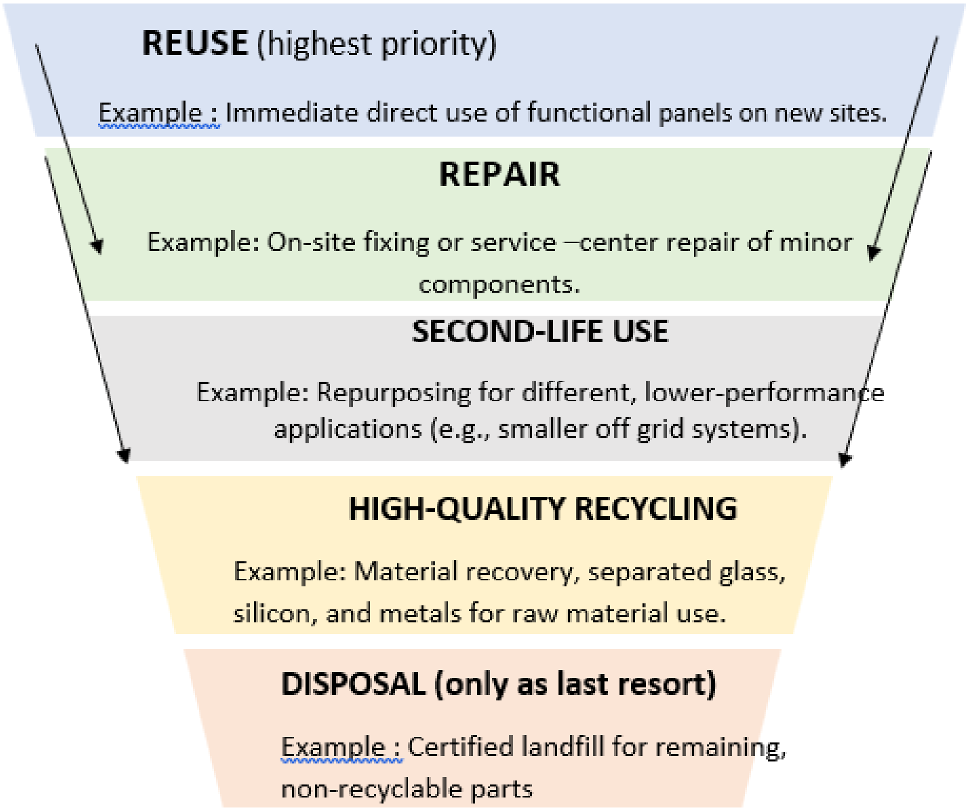

Figure 3. Circular economy hierarchy for solar panel end-of-life management

Circular economy generally tends to be hierarchical with the reuse/repair phase preferred to recycling and disposal being the last option, as illustrated in Figure 2.2. However, in real scenario, this hierarchy requires suitable infrastructure, coordination and operational planning for the movement of solar panels. Most of the existing PV circular economy research projects do not provide a comprehensive explanation of these actual operational processes.

2.3.2 Circular pathways: reuse, repair, and recycling

Recent research on PV waste is focusing on other circular routes for PV. Up to this point, the focus of many studies was primarily on recycling processes as the end-of-life. But now, the researchers are distinguishing the reuse, repair, second-life use, and recycling options, and attempting to elucidate the context in which to employ each (Ndzibah et al., 2022; Marinna et al., 2025).

For instance, Marinna et al. (2025) have proposed the decision model for PV module reuse. If the solar panels still meet technical requirements and safety tests then reusing them in 2nd life applications rather than recycling them directly may be a better option, according to their study. This is a sort of hierarchy in that panels that are still working should not be deemed as “waste” by default.

The IEA PVPS report for second-life PV modules also clarifies that re-use systems must undergo a proper testing and qualification process, have re-use markets and regulations in place to function well (Aspects, 2026). Not only is the reuse an environmental idea, but it is also an economic one. It also must be available in the form of organized infrastructure, with defined standards and coordination between various actors (Aspects, 2026; Marinna et al., 2025). A second systematic review on solar panel re-use certification also states that there needs to be the right rules and regulations in place for re-used solar panels. This should play a crucial role for enhancing the safety, trust and market acceptance of second-life solar panels (Marinna et al., 2025).

The importance of these studies is that they demonstrate that circular economy is not only about recycling percentages in PV systems. They also include the activities carried out for the smooth running of the business such as tests and quality control, certification, data management, coordination between stakeholders etc. Many of these studies, however, only talk about the framework and decision model. They typically are not very descriptive about the process of operation. They, for instance, fail to explicitly describe the flow of panels in collection and testing systems, and the waiting times for panels in various stages.

This means that operational efficiency in circular pathways remains less researched, particularly in countries with longer transport routes such as Finland, and with the specific winter climate conditions, which can significantly influence the recycling and reuse processes (Franz & Piringer, 2020). Clear distinction between reusable PV panels and those that should go directly to recycling in future PV systems that promote reuse and second-life applications will be required in Finland (Marinna et al., 2025; Ndzibah, Cruz, et al., 2022). Unsafe panels can be reused in the market if there are weak testing and sorting systems. Weak testing and sorting may lead to re-use of panels too early or unsafe panels can be re-used in reuse market. This can have a negative impact on resource efficiency and also the trust in SLS.

One of the solar panels, for instance, which has to be removed from the roof of a solar panel farm in rural North Karelia, can first be sent to a testing centre in Joensuu. After successful electrical and safety tests it can also be later transferred and used as second life application in the summer cottage area in Lapland (author example). However, this type of system requires clear decision rules to determine when the panel changes from "waste" to "second-life stock", an organized transport system and a certification process. Although the concepts are referred to in circular economy studies, information on operational details is not available in a clear manner.

Table 3. Selected circular economy studies on PV and their gaps.

Author(s)	**Focusing on the right things**	**Good at taking action and moving forward**	**Weakness / gap noted**
(Ndzibah, Cruz, et al., 2022)	End-of-life analysis and circular economy	Describes reuse and repair together.	Not specifically geared towards Nordic or cold-climate conditions.
Marinna et al. (2025)	Reuse decision-making framework	Reuse decision model, ideas for certification.	Shallow discussion of logistics and waiting time.
(Oreski et al., 2026)	Second-life PV modules	Highlights testing, qualification and infrastructure needs	No detailed indicators for operational time or cost

According to this comparison the interest in the circular pathways for a PV system is growing. However, few studies have been conducted that link these decision models to some real logistics system and tangible operational results. Therefore, when combining circular economy with lean management, it could be helpful: lean is more focused on the process flow and focus on minimising operational waste and time (El Hafiane et al., 2025; Teixeira et al., 2025a).

2.3.3 Limits of the circular economy when used alone

Although the concept of circular economy is a central theme of this thesis, it can also be seen that there are a number of restrictions on circular economy. The notion of a circular economy helps to reveal the objectives of reusing, repairing, recycling and implementing resources efficiency, but it does not offer numerous specific tools for solving the daily issues encountered within reverse logistics systems (Luu et al., 2025). For instance, one PV end-of-life contribution recycling study and material demand presents, illustrates that, properly managed, recycling can contribute to resource efficiency and lower environmental impacts (Luu et al., 2025). Environmental benefits of recycling could be reduced under such operational conditions.

This is crucial for this thesis. Circular economy provides guidance and clarity on how the system should be. For instance, less waste, longer use of materials, and better recovery of valuable materials. At a practical level, however, circular economy does not clearly outline how activities should be organised to achieve the aforementioned goals (Lindahl, 2024; Luu et al., 2025). In addition, I read literature and found that many scenarios' studies were based on literature models and theoretical assumptions rather than real operational data. Due to this, some conclusions might appear to be fine in theory but challenging in practical process situations (Iseri et al., 2025).

Another is that while policy and technical aspects of the circular economy are emphasized in the context of PV, human and organisational aspects are less emphasized. In many studies, the issues such as skill of workers, communication between actors, facility layout and coordination of collection routes are not discussed that much (Iseri et al., 2025). However, these factors can be significant operational issues as they can cause delays, unnecessary movements and errors within actual recycling systems. Even with robust recycling policies and technologies, recycling can fail to deliver expected circular economy outcomes if these real-life operational challenges are not resolved.

Due to these constraints, the use of the circular economy is not sufficient, as this thesis argues. They need another structure in conjunction with it. The principles of the circular economy are primarily the ones that are used to argue why panels should not be thrown away, but reused, repaired or recycled. But another method must be used to grasp what these operations should be in practice. Lean management can be a tool to achieve this as lean is aimed at cutting waste in processes and enhance operational flows (González-Reséndiz et al., 2018; El Hafiane et al., 2025). Value stream mapping is one of the lean tools which can be used to discover waste such as waiting time, transport waste, unnecessary handling and defect within the collection and testing system. In more ordinary approaches to the circular economy, these working parameters are not described in much detail. Therefore, next section will discuss about lean management and how lean principles and tools can be used to support the implementation of practical circular PV recycling systems in Finland.

2.4 Lean management principles and their relevance to PV recycling

2.4.1 Lean as an operational lens

Lean management typically is described as a tool to identify and eliminate waste within processes. Main idea of lean is improving flow and focusing more on activities which create value (González-Reséndiz et al., 2018). Lean has been applied to eliminate wasteful activities within operations, such as unnecessary movement, waiting time, defects, over-processing and other waste activities in various industries (González-Reséndiz et al., 2018; Teixeira et al., 2025a).

There are some studies on the combination of lean and circular economy, which say that lean can also contribute to the goals of circular and environmental economy. When applied properly and not as just tool collection (El Hafiane et al., 2025), this is possible because lean will seek to minimize process waste, optimize the use of resources and make operations more efficient.

For PV end-of-life system, lean management can be considered as a way of thinking about the motion of solar panels through the recycling chain. Typically, reverse PV process involves decommissioning, collection, transport, consolidation, testing, sorting, dismantling and material recovery steps prior to the final recycling/reuse. There are lots of operational wastes that may occur at these stages. These include extended durations in the waiting line, multiple handling, suboptimal workplace design, communication shortcomings, and degradation of information and materials (Iakovou et al., 2024; Franz & Piringer, 2020).

Organisations are encouraged to carefully map the process flow, and determine the location of non-value activities within the process (González-Reséndiz et al., 2018). Once these wastes are identified, process improvement can be implemented to eliminate wastes and enhance process flow. However, most lean studies continue to be centred around manufacturing factories or the general logistics system. The types of PV waste management systems that they typically do not target is a particular country. While numerous studies address the benefits of general leanness such as reduced lead time, reduced inventory and improved efficiency, their findings are less clear when addressing the application of lean thinking in the case of long reverse logistics systems with small and dispersed volumes of PV waste and challenging environment, such as Finland (Teixeira et al., 2025a; El Hafiane et al., 2025).

Hence, the application of lean management in PV recycling is still mostly at the conceptual level. There is still more practical work to be done to implement lean thinking into end-of-life operations in PV context, particularly in the context of Finland. One of the important objectives of this thesis is to accomplish this.

2.4.2 Lean tools and operational waste in PV systems

There are two particular lean tools which are important for this thesis. These are value stream mapping (VSM) and 6S workplace organisation. The Value stream mapping is used for demonstrating materials and information flow throughout the process from start to end. The process can begin with the dismantling and collection of end-of-life PV systems and proceed with transportation, testing, sorting, dismantling, material recovery and reuse/recycling of the dismantled components. Clearly mapping this type of flow makes it easier to identify where unnecessary activities are occurring. It can indicate, for instance, where panels wait for too long, where additional handling occurs or where the length of the transport becomes too great. All these are identified as operational wastes in lean management (González-Reséndiz et al., 2018; Teixeira et al., 2025a).

Problems of long transportation distances, weak collection systems and lack of coordination are addressed in many studies on PV, yet most do not visualize the whole process flow together (Iakovou et al., 2024; Franz & Piringer, 2020). As a result, operational issues are not always viewed as a part of a whole system, but rather as individual issues. In the context of Finland, let's take the example of value stream map of solar panels collected from the solar farm close to Oulu. Flow can occur in this way in current process:

Step 1: Solar panels are taken out from the site and kept for around 14 days till the solar panels are collected in requisite numbers for transportation. This means that there is waste waiting time.

Step 2: The collection of panels and their transportation are conducted by the local transport company, and transported around 200 kilometres to the consolidation point in Kemi. This leads to transportation activity.

Step 3: Unloading of panels and quick inspection and reloading for approximately 7 more days when sufficient panels are collected to be transported by a bigger truck in Kemi. This will result in delay and additional handling.

Step 4: Panels are loaded again into long distance truck and moved approx. 600 km to the recycling plant near Helsinki.

Step 5: Panels are then placed in waiting until 3 more days have passed, and the recycling process begins.

In the above case, the total lead time is approximately 24 days between the time of de-commission and time of processing. The amount of transport distance also increases to approximately 800 kilometres per batch of panels. There is potential to further stream-line the value stream map in the future by eliminating some of the steps. The panels can be transferred directly from the Oulu area to Helsinki on a fixed weekly basis, for instance. This may eliminate an additional storage stage in Kemi, minimize waiting time and elim-inate unnecessary handling activities. Although it is not possible to calculate the exact financial savings here, lean thinking indicates that this type of improvement is able to decrease the transport waste, waiting waste and the operational cost in the Finland PV recycling system.

The other 6S workplace organisation is an important lean tool. Typical lean systems typ-ically involve 5S – Sort, set in order, Shine, Standardise and Sustain. In some industries another “S” is introduced for Safety, it becomes 6S approach (González-Reséndiz et al., 2018). The 6S approach is significant for PV recycling as it contains broken glass, electrical components and potentially dangerous dust or fragments. Safety issues can also be fac-tors in diminishing efficiency due to re-work, operational interruptions and delays caused by accidents. In simple practical way, for example, in PV sorting facility in Tampere, 6S can be applied as:

Sort: Remove crystalline silicon panels and those that are mainly glass immediately after reception. Fractured panels may be transferred to a clearly-marked broken area.
Label the containers: Aluminium frames, copper wires and mixed plastics. Arrange tools near to work station to eliminate unnecessary round trips.
Shine: regularly clean working areas to minimise dust and contamination of valuable materials.

Standardise: Have basic checklist of tasks for workers for each shift. This could be in checking labels, returning tools or inspection of broken glass areas, etc.
Sustain: Conduct brief weekly inspection and team meetings to discuss issues to ensure good practices.
Safety: Safety glasses and cut resistant gloves should be worn. Any broken panels must be stored in safe containers and any emergency exits maintained in good order and in good light.

Currently, there are still some smaller-scale recycling or pilot facilities with poor organisation systems, especially in the winter months, where snow and ice cause additional logistical challenges in the outdoors (Franz & Piringer, 2020). Rough edges and slippery floors can also pose a danger of accident. In Finnish PV facilities, the 6S approach can be used to enhance the sorting's accuracy, decrease the occurrence of small injuries and increase the stability of the PV operation. This can also enhance recovery value of the valuable materials. Although the figures given below are only examples, they demonstrate the potential for practical improvements in real PV recycling in Finland by applying lean tools.

2.4.3 Kaizen for continuous improvement

Kaizen is continuous improvement over time, small improvements over time. Kaizen is not one big change in lean management. Rather, it emphasizes a multitude of small improvements that are implemented on a regular basis jointly among workers and managers (González-Reséndiz et al., 2018). These changes are typically low cost, simple, but over a long period of time can yield significant process benefits. Kaizen can tackle practical issues during the operation in PV recycling systems. For instance, it can eliminate delays in testing, handling damage to the testing panels and winter damage issues.

The following simple model can be envisioned in Kuopio, Finland, in a small PV collection centre. There, it takes about 25 minutes to test one solar panel for possible reuse. One of the reasons is that the testing equipment is located approximately 15 metres away from unloading area. Workers during kaizen discussion suggest that the testing cart can be moved closer to the unloading area for the panel to be tested right after unloading. This little change is virtually insignificant, but test time will cut down from approximately 25 minutes to approximately 12 minutes per panel. Once things have improved, workers continue to use new layout as standard working practice.

Another kaizen activity might be to decrease the damage to the panels at a later stage. Rubber padding can be applied to unloading ramp and the stacking method can be changed during snowy and icy days. These are minor changes but could help to decrease panel breakage and processing time over the months without a significant investment in technology. As this example demonstrates, the operational efficiency can be increased significantly by the small, practical improvements the workers make, even in such a cold climate and far distant country as Finland.

Table 4. Lean tools and their possible use in Finnish PV recycling.

Lean tool	Purpose	Example in Finland PV recycling
Value Stream Mapping (VSM)	Show material and information flow and identify waste	Map Oulu → Kemi → Helsinki route and reduce waiting time from around 21 days to about 3–5 days
6S	Improve workplace organisation, safety and reduce errors	Tampere sorting facility using labelled bins, safety equipment, tool boards and weekly inspections
Kaizen	Support continuous small improvements from workers	Kuopio collection hub moving testing cart closer and reducing panel breakage during winter

This table indicates the possible use of lean tools in Finland PV recycling environment. Lean management is more than just management theory. It can also be linked to actual transport routes, facilities and activities in operation covered in this thesis.
Next section is about lean tools such as VSM, 6S and Kaizen with Finnish examples, which will then be followed by a conceptual framework that integrates PV recycling, circular economy, and lean management.

2.5 Linking PV recycling, circular economy, and lean management

2.5.1 The three-part relationship

The literature examined in this chapter shows that there is a strong link between PV recycling, the concept of circular economy and lean management. The main application area considered in this thesis is PV recycling since the real system where PV, recycling activities and end-of-life processes are studied is PV recycling.The strategic direction of the system is provided by circular economy. It provides an explanation as to why it is important that solar panels should be re-used, re-conditioned to serve second-life, or high-value re-conditioned for re-use in new solar products rather than being directly disposed of (Lindahl, 2024; Ndzibah et al., 2022; Europa, 2024b, 2026). The overall objective is to extend the lifespan of materials and products, and minimize waste.

This relationship is more of an operational mechanism for lean management. Lean is a streamlined approach that aims to minimize waste within the process and to enhance the efficiency of the operation through some tools such as value stream mapping, 6S and kaizen (González-Reséndiz et al., 2018; El Hafiane et al., 2025; Teixeira et al., 2025a). This thesis suggests that circular economy is insufficient because most of the studies of circular economy remain at strategic level. They discuss the desired goals, but usually not the clear way in practice how operational daily activities, such as collection, testing, sorting and transport, actually work (Luu et al., 2025). Meanwhile, lean management that is not circular can also pose problems. Lean could enhance the efficiency of the wrong system, such as making the “collect and dispose” process faster, rather than by promoting a re-use or high-value recycling one (El Hafiane et al., 2025; Teixeira et al., 2025a).

This makes the combination of circular economy & lean management to be significant for Finland PV recycling system. Lean management will optimize the operational aspect of the system, and circular economy will outline the direction of the system.

2.5.2 The mediating role of operational efficiency

Lean management in this thesis is not considered as a direct sustainability outcome. Rather, lean primarily focuses on first improving operational efficiency. Once operational efficiency is enhanced, sustainability performance can also be enhanced later. The use of lean tools such as value stream mapping, 6S and kaizen at the PV recycling chain may minimize various wastes occurring during the operations. Some of these include minimizing lead time in transporting waste, minimizing waiting time at collection points, and decreasing unnecessary handling, sorting accuracy and safety issues (Iakovou et al., 2024; Franz & Piringer, 2020; González-Reséndiz et al., 2018).

These operational enhancements can then be used to help achieve more sustainable outcomes. For instance, higher process efficiency can lead to higher material recovery rate, lower GHG emission per tonne of PV waste and lower operation cost per tonne of PV waste handled (Wei et al., 2025; Luu et al., 2025). Due to this relationship, operational efficiency is considered as a mediating variable in this thesis between lean management practices and sustainability performance. The conceptual relationship is as follows:

Lean management practices → Operational efficiency → Sustainability performance (Teixeira et al., 2025a; El Hafiane et al., 2025).

Other studies from the other sectors also indicate similar idea. The studies found reveal that the improvement of the environmental and economic performance of lean management occurs primarily through operational process improvements, rather than automatically (Sasso et al., 2025; Ghaithan et al., 2023). This mediating role is crucial in PV recycling systems, because it allows to identify where lean interventions should be targeted and which operational measures to expect to improve once implementing lean.

2.5.3 Conceptual framework figure

This thesis has a conceptual framework, which is illustrated in Fig. 2.3. The framework helps link lean management, the operational efficiency and sustainability performance within the context of Finland PV recycling.

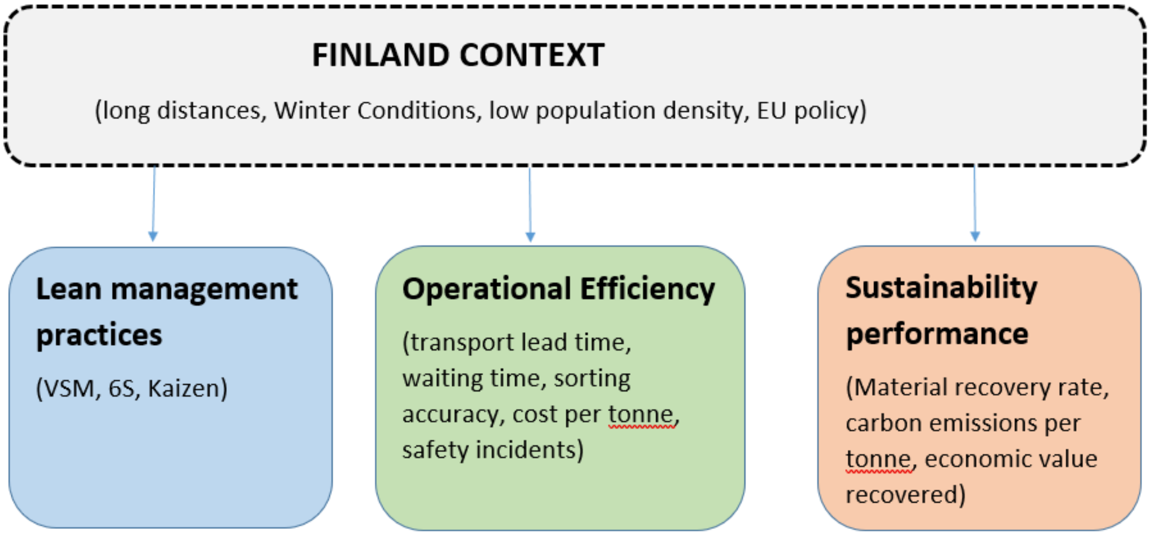

Figure 4. Conceptual framework linking lean management, operational efficiency, and sustainability performance for PV recycling in Finland

Lean management practices, such as value stream mapping (VSM), 6S and kaizen, are located on the left side in the framework. It is expected that these lean tools will help improving the efficiency of the PV end-of-life systems. This relationship is shown with arrow moving from lean management practices towards operational efficiency. Operational efficiency is defined as various aspects of the operational processes including lead time of transport, reduction of waiting times at the collection centres, reduction of unnecessary handling activities, sorting accuracy, and safety performance during operations in this thesis.

Once operational efficiency advances, sustainability performance is anticipated to also enhance. This correlation is depicted with another arrow that goes from operational efficiency towards sustainability performance. Some examples of sustainability performance in this thesis are material recovery rate, carbon emissions per tonne of PV waste and economic value recovered from materials (Wei et al., 2025; Luu et al., 2025). Finland context is also taken into account as the important factor in the framework. The dashed arrows from the box ‘Finland’ indicate that the application of lean and the potential for operational and sustainability improvements in Finland can be influenced by long haul transport distances, winter conditions, low population density and EU waste regulations (Europäisches Patentamt, 2025b; Franz & Piringer, 2020).

2.5.4 Remaining gap and how this thesis fills it

Despite the increasing research into this area, there are still gaps in literature. There are no holistic and measurable indicators or Finnish-based applications for the integration of the circular economy and lean management in PV recycling systems available in the existing studies. The previous studies focus on the different topics of PV waste, circular economy and lean management individually. Little guidance is available regarding the combination of lean and circular approaches within PV recycling systems in countries with challenges related to distance, population density and winter conditions, such as Finland (Pvps, 2012; Europa, 2025b; Iakovou et al., 2024; El Hafiane et al., 2025).

Based on this literature review there exist also no previous research that would clearly link lean tools such as VSM, 6S, kaizen, to the Finnish PV reverse logistics chain and measure operational and sustainable indicators together.

This thesis attempts to overcome this, in three primary ways.

First of all, this thesis translates the lean tools such as VSM, 6S and kaizen into the context of recycling of PV's in Finland by providing concrete, step-by-step examples based on the collection, sorting and transport processes.

Second, the thesis sets out to determine measurable criteria for PV end-of-life systems' operational efficiency and sustainability performance. These are such as lead time, transport distance, waiting time, sorting accuracy, recovery rate and emissions per tonne of PV waste.

Third, the development of the framework is done in a systematic literature review approach. The selection of studies and synthesis of themes is done based on PRISMA, in order to ensure that the framework is based on current literature and not only on theoretical assumptions (Wei et al., 2025; Marinna et al., 2025; Teixeira et al., 2025a). Therefore, the centralities of this thesis are a combination of integration, operationalisation and indicator development for measurable indicators in Finnish PV recycling systems.

3. Methodology

3.1 Introduction

This chapter details the process of conducting the SLR for this thesis. It covers research design, research question, scope of the study, search strategy, study selection process, quality assessment, data extraction, data synthesis and also methodological limitations are discussed. The primary focus of this chapter is to provide an explanation of the review process in a clear and transparent manner, to make it easy for others to understand the methods used in the study and be able to replicate the process if necessary.

3.2 Research design

The research design that is applied in this study is systematic literature review (SLR). This method was chosen due to the requirement of information from multiple related topics such as PV recycling, circular economy and lean management. Previous experiences and knowledge in these topics are dispersed in various fields of research and hence, systematic literature review would be appropriate for summarizing and synthesizing previous knowledge rather than primary data collection.

This study also applies the PRISMA approach in 2020 that emphasizes transparency of reporting in systematic reviews. PRISMA aids in making the process of searching, selecting, assessing and synthesising studies more comprehensible in the review process.The thesis is a thematic synthesis, rather than a meta-analysis, of qualitative studies. That is because selected studies employ various research methodology. Technical experiments, reverse logistics modelling, policy analysis, conceptual discussion or review approach are used in some studies. Quantitative meta-analysis is unsuitable for this type of research due to the lack of a common statistical result that is found in these studies.

Thematic synthesis is better suited for use because it enables the condensation of various ideas, operational problems and patterns derived from literature into themes and then research questions can be used to analyse the themes. Following Saunders et al. (2019), methodology of this thesis can also be explained using Research Onion model. The research philosophy is primarily interpretative, as the study aims to interpret the different researchers' discourses on PV end-of-life management, circular economy and operational efficiency and lean management.

This research approach is inductive since the conceptual framework was developed based on reviewed literature and not testing one research hypothesis from the start. Research method applied in this research is Systematic Literature Review. Qualitative research is methodology of choice. Time horizon for literature review is cross sectional, up to early 2026. The main methods used in this study are: PRISMA study selection and thematic synthesis.

3.3 Research question and scope

Main research question of this thesis is:
How can lean management principles be used to improve operational efficiency and sustainability performance in solar panel recycling systems in Finland?

The review primarily concentrates on the studies related to PV end-of-life management, recycling system, circular economy, reverse logistics, operational efficiency and lean management of waste or recycling processes. The majority of the sources that have been chosen are peer-reviewed journal articles and technical and policy reports. Reports from European Union and IEA PVPS were also included to include crucial information regarding PV waste projection, second life and producer responsibility systems. Main geographical focus of this thesis is Finland. However, if some foreign studies presented useful concepts, models or evidence which could support the Finnish PV recycling context, these were also included.The studies that only mention PV production and/or electricity generation were generally not included in this review unless they are specifically related to PV end-of-life management.

3.4 Search strategy

3.4.1 Search logic

Search strategy of this thesis was based on three main concept groups.

1. PV end-of-life and recycling

This group included terms like "solar PV", "photovoltaic", "recycling" and "end-of-life".

2. Circular economy and sustainability

This group included terms such as "circular economy", "reuse", "second-life" and "resource efficiency".

3. Lean management and operational efficiency

This group comprised such terms as "lean", "lean management", "reverse logistics" and "operational efficiency".

The following keyword groups were linked together by Boolean operators AND and OR. This helped to expand the search to a wider and more specific combination that related to the research topic.

3.4.2 Databases and sources

Literature search was done from Scopus as the main database as it contains journals related to engineering, environment, logistics and management. All these areas are of significance to this thesis topic.

The databases of Google Scholar and ScienceDirect were also used to cross-check the articles and for finding other articles that may not be available in the Scopus database search.

The European Commission (Europa) website and IEA PVPS publications were used to gather policy and technical reports. These sources were important because they included information that was relevant to PV waste projections, second life systems and producer responsibility context information.

Main database search was carried out in January 2026.

3.4.3 Example search strings

Main search string used in Scopus was:

TITLE-ABS-KEY(("solar PV" OR "photovoltaic") AND ("recycling" OR "end-of-life") AND ("lean" OR "circular economy"))

This search produced 137 records.

To understand wider background literature related with PV recycling, another broader search was also used:

TITLE-ABS-KEY(("solar PV" OR "photovoltaic") AND ("recycling" OR "end-of-life"))

Additional searches in Google Scholar and ScienceDirect used shorter keyword combinations such as “PV recycling” AND “circular economy” and “PV waste” AND “reverse logistics”.

These extra searches were mainly used for checking that important studies were not missed during Scopus search process.

3.4.4 Duplicate handling

All the identified studies were exported in Mendeley for organisation and screening process.

Duplicate studies were checked for by comparison of the title, author, publication data and the information on the DOI. In the course of this, 12 duplicate records were found and deleted.

However, after removal of duplicate records in the final screened dataset, new unique studies in the cross-checked datasets were added which brought the final screened to 137 unique studies.

This process of double checks was significant as it reduced over counting of one and the same study, and made for a fairer review process.

3.5 Study selection

3.5.1 Inclusion criteria

These are the conditions that were used in this review of the studies.

- Printed in English language.
- Peer reviewed journal articles or good quality technical / policy reports.
- Full-text version was available.
- Discussed topics related with PV end-of-life management, PV recycling, circular economy in PV systems, reverse logistics or lean management in waste and recycling systems.
- Had direct or indirect contact with a context related to Finland or Nordic context, at conceptual level.

3.5.2 Exclusion criteria

The studies were excluded if they met the following criteria:

- With only PV manufacturing or PV electricity generation involved, but not with end-of-life management.
- Excited about word "lean" that appeared outside the context of topics.
- Readied word "lean" in unrelated contexts such as lean startup or software development.
- Full-text version was not available.
- Did duplicate studies, very short opinion articles, but non-academic with no evidence.

3.5.3 Screening process and PRISMA flow

Study screening process was conducted according to PRISMA 2020 logic. PRISMA approach helps to explain clearly the process of identifying, screening, evaluating and finally include studies in systematic review process.

Initially, a total of 137 records were found in databases and other sources. Following duplicate checking 137 records were available for screening process.
The titles and abstracts of these studies were then reviewed and screened according to the inclusion/exclusion criteria. Following this step, there were 52 studies that might be relevant.

A detailed review of these 52 studies was then conducted and full text versions were retrieved. Following final full text evaluation, 49 studies were chosen and added to the final synthesis.
The PRISMA flow diagram is presented in Figure 3.1, based on the numbers of studies selected.

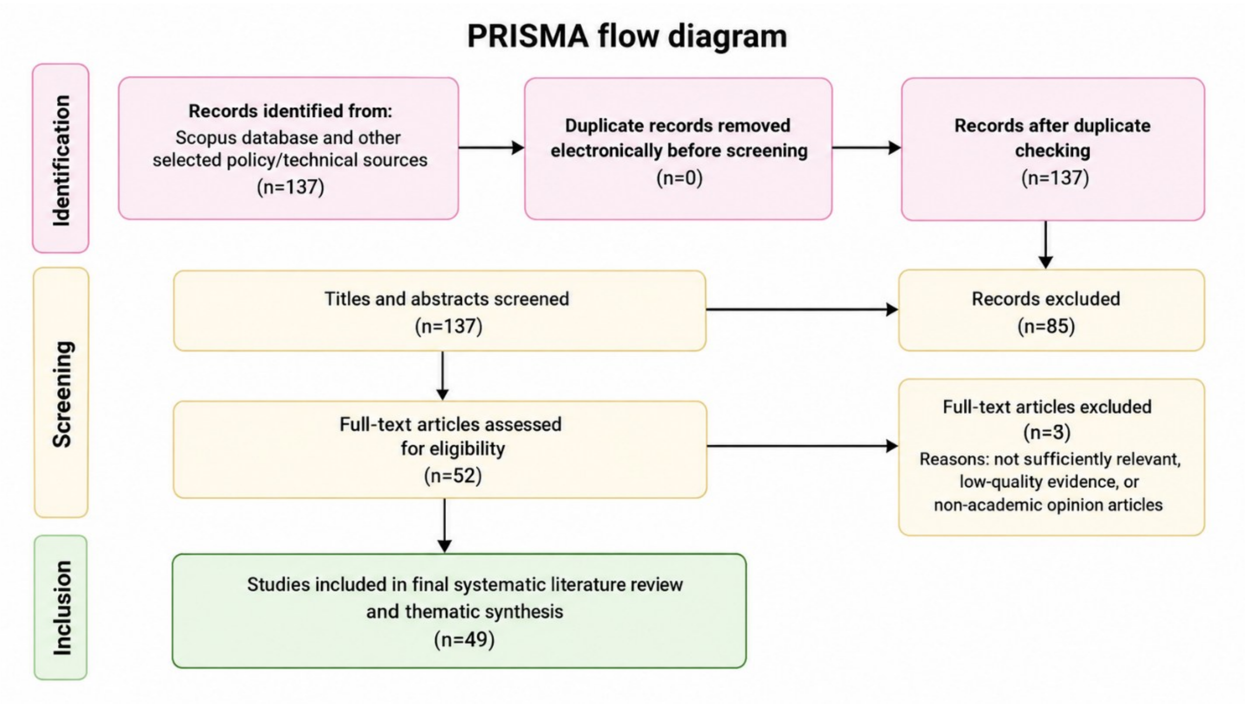

Figure 5. Prism flow diagram

3.6 Quality assessment

Simple 3-point scale was used to check the quality of the selected studies. During the assessment process three criteria were considered:

1. Clarity of research aim and method.

2. Relevance to thesis topic.
3. Strength of evidence.

Studies were judged to have a higher score where research method was clearly presented, there was good linkage to PV recycling and operational efficiency and more robust evidence (experiments, models, case studies, systematic review methods).
More weight was given to studies published in stronger journals especially for peer-reviewed journal articles and studies that included empirical or systematic evidence. The conceptual paper that contained no detailed data, but that supported important explanations of concepts were included, but treated more carefully during data synthesis process.

Organisation's policy reports and technical reports such as European Union and IEA PVPS were considered as grey literature. These reports were mainly used for background information, policy context, regulations and PV waste projections instead of being used as main theoretical evidence. There was no automatic exclusion of studies from the review due to quality assessment. Rather it was used to determine the significance to give to each study in the interpretation and synthesis. For instance, detailed reverse logistics study was seen to support the operational evidence better than a general discussion/commentary paper.

Table 5. Example quality assessment scores.

Author(s)	**Source type / journal**	**Quality score (1–3)**	**Reason**
Wei et al. (2025)	Peer-reviewed journal	3	Clear method, strong recycling evidence and high relevance to material recovery

Iakovou et al. (2024)	Peer-reviewed journal	3	Strong reverse logistics discussion and useful operational analysis
Franz & Piringer (2020)	Peer-reviewed study / contextual source	2	Relevant for Finland context but less detailed empirical evidence
Marinna et al. (2025)	Peer-reviewed journal	3	Clear framework for reuse decision-making and certification discussion
El Hafiane et al. (2025)	Review article	2	Strong conceptual connection between lean and circular economy but limited direct PV focus
Aspects (2026)	IEA PVPS report	–	High-quality grey literature used mainly for background and second-life context

Full quality assessment for all 49 selected studies is included in Appendix B.

3.7 Data extraction

Information from all selected studies was extracted in an organised manner in a structured data extraction table that was created in Microsoft Excel. The same information was documented for each study to facilitate comparisons within studies instead of reading each article individually.

Information on the author(s), publication year, article title, journal/source/s, geographical focus, research method, key concepts, main findings, relevance with Finland and quality score were collected for each study.

The use of this extraction table facilitated literature organization in a more clear-cut manner as well as facilitated thematic analysis during the synthesis stage.

Table 3.2 shows small sample from the extraction table. Full extraction table for all 49 studies is included in Appendix A.

Table 6. Sample of the data extraction table.

Author(s)	Year	Geo-graphical focus	Method	Key findings relevant to thesis
Wei et al.	2025	Interna-tional	Review / technical analysis	Recovery of high-value materials is more difficult than bulk material re-covery; recycling success should not only depend on total recovered weight
Iakovou et al.	2024	Interna-tional	Reverse lo-gistics / sys-tem analysis	Weak reverse logistics systems and poor facility optimisation are major barriers in PV end-of-life manage-ment
Franz & Piringer	2020	Finland / Nordic context	Contextual analysis	Long transport distances and geo-graphic spread increase difficulty of PV waste management in Finland
Marinna et al.	2025	Interna-tional / PV reuse	Decision framework / review	Reuse and second-life systems need testing, certification and organised decision rules
El Hafiane et al.	2025	Cross-sec-tor	Review arti-cle	Lean management can support circu-lar economy goals, but practical oper-ational application is often limited or too general

3.8 Data synthesis

Thematic synthesis method was used to analyse the data collected. Because many studies included in this research used various research designs and methods, this method was chosen. The purpose of synthesis was not to synthesize statistics, but to build themes and patterns, cluster similar ideas, and build analytical themes related to the research question.

The process of synthesis was carried out in three steps.

First of all, open coding was done. Each selected study was read carefully and short codes of description were written according to important findings, ideas/operation problems discussed in the literature.

Some examples of these codes were:

- “transport inefficiency”
- “long distances”
- “lack of reverse logistics planning”
- “second-life certification”
- “low silver recovery”
- “sorting errors”
- “policy support”
- “lean potential”

Secondly, codes that were similar were combined into larger descriptive categories. For instance, codes pertaining to transport, waiting, routing and consolidation were clustered into a single category for transport inefficiencies. Sustainability assessment comprised codes talking about environmental impacts and emissions. Codes related to certification, policy conditions, and market issues were categorized as “policy” and “economic” codes.

Third, these categories were read within the context of the research question and further divided into five overarching themes which were later used in the findings and discussion chapter.

The five final themes are:

1. Recycling and circular economy.
2. Sustainability and environmental assessment.
3. Policy, market and economic analysis.
4. Technological innovation and system optimisation.
5. Material recovery and resource efficiency.

Table 7. Example of codes and their final themes.

Code	Description	Final theme
Transport inefficiency	Long distances, repeated handling and lack of consolidation	Technological innovation and system optimisation
Lack of reverse logistics planning	Weak routing systems and collection structure	Recycling and circular economy / system design
Low silver recovery	Difficulty in recovering valuable materials	Material recovery and resource efficiency
Second-life decision model	Decision criteria for reuse or recycling	Recycling and circular economy
High PV waste projections	Increasing future waste amounts and planning needs	Policy, market and economic analysis
Life-cycle environmental impact	Environmental impacts and emissions from end-of-life systems	Sustainability and environmental assessment

The coding table has been provided to illustrate the linkages of each individual study finding with the final themes for analysis.

The literature findings are then connected to lean management tools and to the context of Finland PV recycling in full coding notes, during the writing process for the Chapter 4.

3.9 Methodological limitations

There are also some methodological constraints that are important in understanding the results of this methodology.
First, only English language sources were reviewed. Therefore, a few helpful reports or studies, which were not available in English, may not have been included.

Second, the review was conducted primarily on the Scopus database, Google Scholar, ScienceDirect and easily accessible policy sources. The fact that some articles or databases are for subscription only, may mean that they have not been included as a result of the search.

Thirdly, one researcher only conducted the quality assessment and coding process. Despite the fact that the same criteria were used to select and review the studies, there is some degree of subjectivity in the selection and interpretation of the studies.

Fourthly, there is no actual test performed in the Finnish PV recycling facility that would have been available, using the conceptual framework presented in this thesis. The framework should thus be regarded as conceptually developed model based on literature and not as a validated operational system. Therefore, it is suggested to see the framework as a model which should be tested and verified in practice. The framework should thus be regarded as a conceptually developed model based on literature and not as a validated operational system; therefore, the model should be tested and verified in practice.

Fifthly, some of the figures of PV waste discussed in the thesis are partly derived from the EU level projects and contextual interpretation rather than official waste forecasts of Finland.

These restrictions are of no effect to the validity of the review. However, they indicate that the results of this thesis can only be interpreted as evidence-based and conceptual statements, and not as well-tested operational statements.

3.10 Chapter summary

In this chapter the methodology used in this thesis is explained. Systematic literature review method and qualitative approach of thematic synthesis was discussed in the chapter. It also clarified the search strategy, screening process, quality assessment and data extraction and coding used in developing the five final themes. In addition, the chapter discussed main methodological limitations of the study. The findings and discussion from the literature review is presented in the next chapter. These results are compared to the lean management, circular economy and PV recycling systems in Finland.

4. Findings and Discussion

4.1 Introduction

The results of the systematic literature review are summarized in this chapter, and the significance of the results for the solar panel recycling systems in Finland are discussed. The chapter is divided into five main themes developed during thematic synthesis process. These themes are:

1. Recycling and circular economy.
2. Sustainability and environmental assessment.
3. Policy, market and economic analysis.
4. Technological innovation and system optimisation.
5. Material recovery and resource efficiency.

Important findings from the literature are first explained for each theme. Then, results is discussed in the context of Finland. Lean management tools such as value stream mapping (VSM), 6S and kaizen are also used to demonstrate the potential for operational improvements and measurable indicators to enable the development of more effective and sustainable PV recycling systems. Finally, this chapter summarizes the contributions from all the themes to the conceptual framework of the thesis and put together the main themes of the operational indicators and sustainability indicators.

4.2 Theme 1: Recycling and circular economy

4.2.1 Main findings

As PV recycling is now considered as an important component of the solar energy system and not merely a small waste issue, literature has revealed this. The amount of PV waste will grow significantly in Europe and worldwide as PV panels get older and near the end-of-life stage, as noted in earlier reports and in newer studies. As such, many studies describe the need for organised end-of-life management systems rather than for simple disposal and/or temporary handling systems.

Most of the researchers also talk about PV recycling by the circular economy approach. It is better to consider alternatives to direct landfill disposal for reuse, repair, second-life use and high-quality recycling (Lindahl, 2024; Ndzibah et al., 2022; Europa, 2024b, 2026). The recent studies related to reuse decision making and second-life PV modules have outlined the importance of testing, certification and simple decision rules before reusing reused PV modules (Aspects, 2026; Marinna et al., 2025). Panels that don't pass these tests should enter into the recycling process. In general, it is accepted in the literature that PV recycling should be a part of a larger system of the circular economy. However, the majority of studies have not been clear about the practical way of organising such a system at country level.

4.2.2 Interpretation for Finland

The results indicate that PV recycling does not need to be considered solely as the last step in technical recycling for Finland. It should form part of a broader circular economy approach that relates to solar energy systems. It is already well documented that waste from PV will grow significantly in the coming years in Europe. However, while the size of the installed solar PV capacity in Finland is still smaller than in some central European countries, the volumes of PV waste in Finland are expected to grow as well, seeing that the country is part of the EU solar market.

Finland also has some special conditions which can make PV end-of-life management more difficult. If the system planning is inadequate, long transport distances, low population density outside the big cities and bad weather in the winter could lead to an inefficient and expensive recycling process.

Therefore, few recycling plants can only support the reuse, second-life use and high value recycling. There is also a need for organised collection systems, testing facilities and routing networks in Finland which would be able to handle the scattered PV installations and the seasonal transport conditions. Meanwhile, expectations towards circular economy are growing in Finland and in the European Union. As a result, it is not sufficient in the future that only minimum waste requirements are met. PV recycling systems also need to demonstrate that they actually do extend the life of solar panels and that they are able to recover the value of the materials in an efficient manner.

4.2.3 Lean application and indicators

Value stream mapping (VSM) can be used from the lean management perspective to design more organized circular PV recycling system in Finland. VSM can be used to visualize full flow of solar panels across the re-use, second life and recycling pathways.
For instance, solar panels that are removed close to Oulu must first pass through the stages of temporary storage, collection and testing before being determined to either be reused, utilized for second-life applications or recycled near Helsinki. In current-state value stream map, the panels remain in installation site for approximately 14 days, they are then moved to regional consolidation centre for an additional 7 days and finally to the recycling centre for about 3 more days before processing begins. The total transport distance can also be approximately 800 kilometres, in addition to various handling activities.

An improvement of this process could be achieved with the future-state VSM, which involves direct collection of waste from Oulu area to a single testing & sorting centre every week. Then these operational rules could be clarified and the panel may be put into reuse, second life utilization or recycling. This better flow can lead to a decrease in the total lead time from approximately 24 days down to approximately 5 days, and also eliminate one unnecessary handling step.

Important indicators in this theme include:

- transport lead time (days)
- number of handling activities
- percentage of panels sent for reuse or second-life use
- percentage sent directly for recycling
- cost per tonne (€) during end-of-life process

The improvement of these indicators by process redesign based on VSM can facilitate the Finnish PV recycling system to be more efficient and also more circular economy and lean management friendly.

4.3 Theme 2: Sustainability and environmental assessment

4.3.1 Main findings

The focus of studies related to sustainability and environmental assessment is on the environmental impacts of PV recycling and end-of-life systems. It is explained in many life cycle assessment (LCA) studies that recycling can help minimise environmental impacts as recovered materials can be used to replace some of the production of primary raw materials (Luu et al., 2025; Wei et al., 2025).

But literature also tells us that the benefit to the environment is much related to the system conditions. The collection efficiency, transport distance, recycling efficiency and energy consumption are all factors that impact on the overall sustainability outcome.
If transport distances are large, collection network is weak or recycling centres are very energy intensive with respect to the recovery of valuable materials, some studies caution

that recycling might not always be a large environmental gain. As a result, it is not sufficient to merely proclaim “recycling is environmentally good” – literature states. It is also important to carefully monitor actual system operation indicators under various system conditions. Indicators such as the greenhouse gas emissions per tonne of PV waste, recovery efficiency and energy use in PV recycling operations are thus discussed in many of the studies.

4.3.2 Interpretation for Finland

The sustainability results are of great significance in Finland. The transport distances in Finland are long, and the PV installations are geographically distributed, with cold weather. This can result in increased transport emissions and the use of energy in operation, as compared to countries with recycling facilities and installations more centrally located. The environmental benefit of PV recycling in Finland not only relies on the technology for recycling, but also on the efficiency of the entire operational system.

Environmental performance could be significantly lower if there are long distances to transport the solar panels in small batches, they are stored in the winter for long periods of time and then transported through an inefficient recycling process. Due to this, PV recycling systems with both high material recovery and reduced transport and energy emission is required in Finland. Operational waste within the system must also be minimized in order to support the objectives of the climate and circular economy of Finland in the right way.

4.3.3 Lean application and indicators

In the Finnish PV sorting and pre-treatment facilities, the extended 6S lean approach can be used to enhance the sustainability performance. A good example could be PV sorting centre in Tampere. Efficiently separating different types of panel and labelling bins for different materials, whether aluminium, copper, plastics or glass to keep work areas clean and to standardise tool locations and procedures for safety are all made easier with 6S. Safety precautions and activities such as wearing cut-resistant gloves and using puncture-resistant containers can also play a part, as these contribute to additional waste and rework in case of an accident or damaged equipment.

With enhanced organization and process flow, panel breaking and contamination can be minimised. This results in more materials that can be recovered and reduced in mixed waste production. This will help to enhance the quality of the material recovered and to lower the emission per tonne of PV waste processed.
Important indicators in this theme include:

- sorting accuracy (%)
- material recovery rate (%)
- carbon emissions (kg CO_2 equivalent) per tonne of PV waste
- amount of contaminated or mixed waste generated
-

In other words, if the accuracy of sorting in Tampere facility can be raised from approximately 80 percent to approximately 95 percent, the quality of recovery would get better and more energy would be saved in processing contaminated materials. This would help in the operational efficiency as well as environmental sustainability.

4.4 Theme 3: Policy, market and economic analysis

4.4.1 Main findings

Policy and market conditions and economics are discussed in the literature and it is revealed that PV recycling systems are significantly influenced by these. EU directives, producer responsibility systems (PRES) and national waste regulations are important factors that influence PV EOL management systems, as explained by many studies (Europa, 2024b, 2025b; Aspects, 2026). Studies also reveal that operating costs of existing PV recycling methods are high and the value of the materials recovered is still low.

There are a number of reasons for this, including the fact that the waste volumes from PVs are still in a process of growth and markets for some recovered materials are not fully mature. Studies on reverse logistics and global supply chains also outline the fact that there are no well-organized collection systems and optimized recycling systems in many countries. Limited and deficient data on PV waste flows, as well as weak enforcement, also complicates and costs the planning of systems (Iakovou et al., 2024). Based on this, some researchers suggest that more policy support and better market mechanisms are required for economic sustainability of circular economy business models for PV recycling in the future.

4.4.2 Interpretation for Finland

The results are useful to Finland in their current context as well as in the future.
The PV waste management is linked to the European Union regulatory framework, which is already in place in Finland, under the WEEE-type regulations and producer responsibility systems. However, Finland has a smaller PV market, long distances to transport PV components and a low population density compared to many larger EU countries. Therefore, the collection and recycling fee per tonne of PV waste could be increased if the PV waste collection and recycling routes and facilities are not carefully organized.

Waste regulations based on general recycling targets may not support operational plans and cost-sharing systems, which could result in some operators seeking to lower costs by less frequent collections and/or by holding panels for longer periods or exporting waste out of Finland. This might impact the operational control and also diminish the value of circular economy within Finland. Given this, it is important for Finnish policies and industry to look at PV recycling not just as their obligation. It should also be viewed as a long-term circular economy opportunity that will require investment in organised and coordinated collection and recycling systems.

4.4.3 Lean application and indicators

Kaizen is able to support the economic and operational performance within Finnish PV collection network. Small regular kaizen activities, for example, in Kuopio, can be used to find small practical solutions, which decrease cost, delays and unnecessary movement. Workers and managers can experience issues like extended time for testing, inadequate panel stacking in winter or excessive paperwork when unloading the process. They are able to make low cost ideas when conducting kaizen meetings.

For example:

- moving testing equipment closer to unloading area
- changing stacking method during snowy conditions
- simplifying incoming panel documentation process

While each improvement might seem minor, they all add up to better handling time, decrease panel damage and increase operational flow.
This also assists in minimizing labour and costs of materials, by minimizing breakage.

Important indicators connected with this theme include:

- processing time per panel (minutes)
- collection and pre-treatment cost per tonne (€)
- breakage rate (%) during handling
- labour time used during testing and sorting

With a more efficient workplace layout, for instance, the amount of time spent to test may be reduced from around 25 minutes per panel to about 12 minutes, which would significantly lower annual labour cost per ton. This type of improvement can also make PV collection systems organised in Finland more economically feasible.

4.5 Theme 4: Technological innovation and system optimisation

4.5.1 Main findings

The fourth theme is devoted to technological innovation and optimization of PV recycling systems and reverse logistics networks. Technical studies are about how to make technologies for recycling better, e.g., delamination, material separation and recovery processes. In certain conditions of recycling, high percentage of material recovery, such as glass, aluminium and silicon and metals can be achieved (Wei et al., 2025; Piedrahita et al., 2025).

However, many reviews will account for the fact that recycling technology is not sufficient in achieving a good system performance. The collection, transportation and preprocessing of solar panels prior to their arrival at recycling facility also determine the recycling results (Recycling-results also depend on how solar panels are collected, transported and pre-treated before arriving at the recycling facility (Preet & Smith, 2024; Iakovou et al., 2024).. Research into issues of reverse logistics optimisation also identifies that better outcomes can be realised when economic and environmental goals are taken concurrently into account when planning the system. Such multi-objective network design can be used to enhance the overall performance of a network (Zhou & Li, 2025).

Therefore, more integrated approaches are recommended by many authors to link the different aspects of recycling technology, logistics and conditions of the policies rather than treating them separately.

4.5.2 Interpretation for Finland

The results indicate that in Finland it is always necessary to relate the choices of recycling technology with other system design options. The performance of the system may be poor despite the high recovery rate by the recycling plant, if the solar panels are collected and transported in substandard quality, resulting in damaged panels, delayed deliveries, and inadequate sorting. There are long transport distances, cold winters and uneven distribution of PV installations in Finland. Therefore, a recycling system can not be implemented in Finland context without adapting it for the Finnish context.

A regional collection hub, seasonal scheduling of vehicle movements, and even cooperation with neighbouring countries for certain recycling processes might be needed for the PV recycling system in Finland. Concurrently, digital systems and more information on the PV installations and waste flows can contribute to the optimisation of the networks and transport planning in Finland.

4.5.3 Lean application and indicators

Value stream mapping (VSM) may also be applied at the national system level in order to enhance logistics and recycling activities in Finland in a larger scale level.
A high-level value stream map, for instance, might illustrate the PV panels' flow from rooftop and ground mounted systems to local collection points, regional hubs, testing centres, and finally to recycling centres. Plans can then be made by mapping waiting times, batch sizes and transport routes to find where operational waste is found within the reverse logistics network.

For instance, at present solar panels stay in the regional hubs for about 7 days before they are dispatched to the next hub and so on, but with better route planning and digital tracking systems this can be brought down to about 1 day. The kind of optimisation can help to decrease the waste of waiting and inefficiency of transport.

Important indicators in this theme include:

- waiting time at collection hubs (hours or days)
- average transport distance per tonne (kilometres)
- load factor of transport vehicles (%)
- number of network nodes in typical transport route

- route coordination efficiency

Better these indicators will help in cutting down on the operational costs and also create a more stable material flow for the advanced recycling facilities. This would help to improve the overall recycling efficiency of PVs in Finland and the technological efficiency.

4.6 Theme 5: Material recovery and resource efficiency

4.6.1 Main findings

The last theme is about material recovery and resource efficiency in PV recycling systems. Numerous research papers describe that the crystalline silicon solar panel is primarily made of glass and aluminium. Generally, they can be recovered with ease in the recycling process and recovery rates are high. However, materials such as silver and high-quality silicon are far more challenging to be properly and economically recovered (Wei et al., 2025; Piedrahita et al., 2025).

Some research studies indicate a very high degree of recovery can be achieved by careful control of the recycling conditions. However, there are numerous practical issues in the processing. Contamination and challenging dismantling activities and costs are noted as key concerns. Another issue that has been mentioned in the literature is that not only should the amount of material recovered be considered a measure of recycling success. Even though system recovers primarily glass and aluminium, but also significant amounts of other resources such as silver, true resource recovery may be marginal. In this context several authors, explain that recycling systems need to be more oriented towards the value recovery of materials and broader resource efficiency objectives related to circular economy.

4.6.2 Interpretation for Finland

These results are significant for Finland as it is very dependent on raw materials imports. Efficiently recovering valuable materials from the old solar panels can then be helpful for resource security and help minimize the environmental footprint of the mining and raw material production process. However, this will be effective only if the operational handling is excellent during the collection, transportation, storage and dismantling process. Even with good technology, if the panels are broken while in transit, mixed up together improperly or stored poorly for a long period of time, the quality of the recovered panels can drop.

The definition implies that the Finnish PV recycling system should not only be based on the recycling targets for weight. It also needs to concentrate on maintaining quality of valuable materials even before they get to the end of the recycling process. As far as I know, this is an aspect of operational management where it really counts. This can be caused by poor handling and weak sorting practices prior to the technical recycling process.

4.6.3 Lean application and indicators

The benefits of 6S and kaizen for material recovery and resource utilization in PV dismantling and pre-treatment processes can be observed in the Finnish PV recycling chain. For instance, if a sorting line is using PV cells containing silver, it is possible to implement the 6S principles for better organisation of the workstations. The glass, aluminium frames and solar cells may be collection in separate designated areas. Employees might also have their tools locked in place, and keep their workstations cleaner. Safety is also an issue since broken glass and damaged panels could cause accidents and delays in operations.

Then, small improvements with time can be achieved through the use of Kaizen. Workers might see an increase in order they dismantle materials, a new stacking technique or some new tools that help them minimize breakage and material loss during stacking and dismantling. Overall, these changes can have a positive impact on the quality of recovery and minimize waste.
Important indicators in this theme include:

- recovery rate (%) for glass, aluminium, silicon and silver
- material loss during dismantling (%)
- panel breakage during handling
- number of safety incidents or near-miss cases

For instance, with a few minor process's tweaks, the recovery of the silver could reach to about 85 percent. Concurrently, there might be a reduction in panel damage and minor work accidents. Such enhancement would have a positive impact in terms of resource efficiency and operational safety of Finnish PV recycling systems.

4.7 Summary of the framework and indicators

The results of all five themes are consistent with the conceptual framework outlined above in Chapter 2. As can be seen in the overall framework, lean management practices are initially effective in improving the operational efficiency and this operational efficiency is subsequently beneficial for improving the sustainability performance in PV recycling systems. It is also observed from the results that the role of each theme is different in the entire system.

Most of the research on recycling and circular economy focus on the direction of PV end-of-life systems. Sustainability and environmental assessment studies have more of an emphasis on environmental outcomes which are measurable. Financial and practical feasibility is considered in policy, market and economic studies. The topics of the technological innovation and system optimisation studies are network design, logistical aspects and recycling technologies. Material recovery and resource efficiency studies illustrate the effectiveness of the final recovery of the valuable materials from PV wastes.
In all themes, lean techniques such as value stream mapping (VSM), 6S and the kaizen are used for providing practical solutions to enhance the collection systems, transport routes, sorting activities, workplace organisation and operational flow in Finnish PV

recycling systems. Meanwhile, metrics such as lead time, waiting time, accuracy of sorting, material recovery rate, emissions and cost per tonne help to assess if these benefits are being realised in practice.

Table 8. Summary of lean tools, Finnish applications and measurable indicators.

Theme	**Lean tool applied**	**Finnish example**	**Indicator**	**Example improvement**
Recycling & circular economy	VSM	Oulu → regional hub → Helsinki route redesign	Transport lead time (days)	Reduce lead time from around 24 days to about 5 days
Sustainability & environmental assessment	6S	Tampere sorting facility organisation and safety improvements	Sorting accuracy (%) and emissions per tonne	Improve sorting accuracy from around 80% to about 95% and reduce emissions
Policy, market & economic analysis	Kaizen	Kuopio collection hub process improvements	Cost per tonne (€) and processing time per panel	Reduce testing time from around 25 minutes to about 12 minutes and lower cost per tonne
Technological innovation & system optimisation	VSM	National PV reverse logistics network planning	Waiting time at hubs and transport distance per tonne	Reduce average waiting time from around 7 days to about 1 day

Material recovery & resource efficiency	6S + Kaizen	Silver-focused dismantling line	Material recovery rate (%) and loss rate (%)	Improve silver recovery from around 70% to about 85% and reduce losses

The examples of these values are meant to illustrate and are not a precise prediction. They aim to demonstrate the value of measurable parameters to assess operational improvements of Finnish PV recycling systems. In summary, the results of this chapter indicate that lean management tools could lead the way towards Finland's more tangible operational and measurable improvements in efficiency, cost and sustainability performance as part of the transition towards the circular economy.

5. Conclusion

5.1 Introduction

The conclusion of the thesis is provided in this chapter. It provides a concise overview of the methodology used to meet the research needs and the primary findings of the research. The chapter also discusses practical and policy implications, main limitations of the research and possible directions for future research.
Finally, at the end of the chapter, final reflection about the application of lean management in the Finnish Solar panel recycling system.

5.2 Achievement of research objectives

Objective 1: To analyse existing challenges in PV end-of-life management in Finland
The first goal in this thesis was to analyse the key issues in PV end-of-life management particularly in the context of Finland. Many countries already have similar challenges including a lack of optimized recycling facilities, long transportation distances, limited testing and sorting facilities, and weak reverse logistics systems, as revealed by the systematic literature review (Iakovou et al., 2024; Preet & Smith, 2024).

A few other operational problems were also mentioned in the studies on Finland. Compared to many central European countries, collection and transport operations in Finland may be more challenging due to low population density in the regions outside the cities, long transport distances from the north to the south and the difficult winter weather conditions (Franz & Piringer, 2020).

It is also revealed by the analysis in Chapters 2 and 4 that many of the existing studies concentrated largely on the issues of recycling technologies and policies and fewer studies were undertaken to focus on practical operational activities. For instance, less is said on the number of times solar panels are handled before entering into the recycling process, waiting time at the hubs, or frequency of collection. This objective was realised as a result of the findings made in the thesis, which revealed that there are a lot of end-of-life challenges in the Finnish PV sector related to operational and logistical challenges, which are not technical recycling issues.

Objective 2: To evaluate circular economy strategies in solar panel recycling

The second aim of this thesis was to analyse circular economy approaches related to the recycling of solar panels.

Studies on the circular economy concepts of reuse, repair, second-life use and recycling in PV systems were reviewed in Chapter 2.3.

These studies indicated the importance of the strategic direction of the PV end of life systems to achieve circular economy. The principle is to make solar panels and materials useful for as long as possible, and to retrieve valuable materials from the panels as high quality as possible rather than as waste.

It was also revealed from the literature reviews that many different views on the circular economy remain on a general or policy level. There are numerous studies that outline the desired objectives to be met but none that gives a clear idea of how things should be done in practical activities such as testing, transport routing, sorting and workplace organisation in real systems.

This becomes an even more important in countries such as Finland, where distances are long and winter weather conditions are tough.

Therefore, the thesis stated that the objectives for the circular economy are of value, but cannot be the sole measure. The flow of circular economy into action requires also practical operational planning, not to leave it as a mere policy discussion without action.

That objective was fulfilled thanks to the critical analysis of the circular economy literature with PV systems, which demonstrated that circular economy can be used to understand the “why” of the system, while many questions concerning its operations remain unanswered.

Objective 3: To examine the role of lean management in improving operational efficiency

The third aim of this thesis was to look into the potential of lean management to enhance the operational efficiency of PV EOL systems.

Lean tools, such as value stream mapping (VSM), 6S and kaizen, can be put into practice in the PV recycling environment in Finland using practical examples, as was demonstrated in the chapters 2.4 and 4.

The value stream mapping was used to illustrate the potential path of solar panels to be transported from Oulu via regional hubs to the recycling facility that is close to Helsinki. The examples also demonstrated the potential to further shorten the lead time and improve the flow of the operations through redesigning transport routes and the reduction of unnecessary handling.

The long-term 6S approach was discussed with an example of sorting facility in Tampere. The benefits of improved workplace organisation, separation of materials and safety procedures highlighted in this example are enhanced sorting accuracy and reduced contamination and downtime.

The Kaizen was also discussed based on an example of collection hub in Kuopio. In this case, workers recommended minor practical solutions which included relocating testing equipment to be near the unloading area, and better stacking techniques in winter. These changes reduced the time needed for testing, reduced panel break and did not involve costly investments.

In all these cases, lean management has been linked to measurable parameters, such as lead time, waiting time, sorting accuracy, material recovery rate, and safety incidents and cost per tonne.

Therefore, the aim was addressed by demonstrating in a way that lean management can be used to solve many operational issues which are not entirely covered in strategic circular economy discussions.

Objective 4: To develop a conceptual framework integrating lean and circular economy approaches for Finland

The fourth aim of this thesis was to create conceptual frameworks for the combination of lean and circular economy for the Finnish PV recycling systems.

In Chapter 2.5, the conceptual framework (Figure 2.3) was introduced. The framework reveals that operational efficiency is affected by lean management practices and that the operational efficiency as a whole determines the sustainability performance within PV recycling systems.

The conditions that are important for Finland are also included in the framework, for example: long transport distances, winter weather, low population density, EU waste policy environment.

In this scheme, PV recycling is regarded as the primary application sector of the system, while the circular economy is considered as the strategic direction and lean management as the operational tools for enhancing the system (Teixeira et al., 2025a; El Hafiane et al., 2025).

The framework of organising the five main themes from literature review was used in Chapter 4. These themes were then linked to operational and measurable indicators and lean tools.

Also, Table 4.1 presented some practical examples of the applications of VSM, 6S and kaizen in a context such as Oulu, Tampere, Kuopio and bigger Finnish reverse logistics networks. Examples of improvements were minimising lead time, reducing waiting time, increasing the sorting accuracy and material recovery rates.

To achieve this objective, an integrated framework linking the goals of the circular economy with lean operational tools in the context of recycling PV in Finland was developed.

5.3 Contribution to knowledge

This thesis contributes to the knowledge in three major ways.

The thesis offers, based on this literature review, for the first time a thesis that operationalises the lean management tools, such as VSM, 6S and kaizen specifically for PV recycling in Nordic conditions, with examples from various parts of the reverse logistics chain in Finland.

Second, an operational efficiency and sustainability performance measurement is proposed for PV end-of-life systems. These indicators include:

- transport lead time
- waiting time
- number of handling steps
- sorting accuracy
- material recovery rate
- emissions per tonne of PV waste
- cost per tonne handled

Third, it is the development of integrated framework of circular economy and lean management. The theme in the strategic direction is circular economy and the operational mechanism is lean management.
The study fills this research gap since a lot of previous research focuses on circular economy or lean separately and seldom focus on both in a certain Finnish context of PV recycling.

5.4 Practical and policy implications

The results of this thesis may have some practical uses to companies and organisations involved in PV end-of-life management in Finland.
Value stream mapping (VSM) is a tool that can be used to optimize the collection and transport system for recycling companies and logistics operators. Operators may have collection routes that are routed from far-flung areas, such as Oulu or Lapland, towards regional hubs or recycling facilities closer to Helsinki. Analysis of these routes can help companies to shorten transport lead times, avoid the need for repeated handling and unnecessary storage of panels.

Sorting and pre-treatment facilities, for example in Tampere or other regional facilities, could benefit from the application of 6S methods to optimise the organisation of the workplace, its safety and the quality of sorting. Material recovery performance and downtime can be improved, and contamination can be reduced, with better organisation. Small improvements could be made through the use of kaizen activities in local collection centres, e.g. Kuopio. Simple low-cost solutions may be suggested by workers such as relocating testing equipment to unloading area, better winter stacking techniques, better communication between workers during sorting and transport operations.

Operators can use indicators suggested in this thesis to check if the improvement of these lean actually decreases the waiting time and decreases the lead time, decreases breakage and decreases the operational cost per tonne over a longer period. This study recommends that PV waste policies need not only aim to recycle percentages, but also consider operational efficiency and system design for policy makers and producer responsibility organisations.

In Finland, pilot projects (PP) where lean management and circular economy are applied in actual PV collection or PV recycling facilities might facilitate testing of the conceptual framework in actual production situations.

Policies can also promote companies to report operational indicators like:

- lead time
- sorting accuracy
- waiting time
- material recovery rate
- cost per tonne

In addition to the total recycling amounts. This would allow for a better understanding of the overall system performance (Iakovou et al., 2024; Europa, 2025b).

Nordic waste management studies (Franz & Piringer, 2020) also highlight the importance of the length of transport distances and the cold climate in Finland in regional hub planning and transport routes, or in winter logistics. In total, these activities may aid in developing more efficient, safe and circular PV recycling systems in Finland.

5.5 Limitations of the study

The present study also has a few drawbacks.

Firstly, only English-language sources were considered. For this reason, some useful Finnish/Swedish reports and experiences may not have been taken into account.

Secondly, the literature review was predominantly based on Scopus and policy and technical documents that were easily accessible. There may then be some useful studies or articles that have been overlooked.

Third, one researcher only was responsible for the quality assessment and coding. Although the same process and criteria were carefully applied, there is still some degree of subjectivity that may exist.

Fourth, the concepts and concepts of lean management presented in this thesis have not yet been applied in real case PV recycling facilities or PV collection system in Finland.

Fifth, this thesis uses partly EU-level projections combined with contextual interpretation rather than official national forecasts from the Finnish state in order to estimate the PV waste.Fifth, partly EU-level projections combined with contextual interpretation are used in this thesis for estimating the PV waste, instead of official national projections from the state of Finland.

Due to these constraints, the framework and examples included in the present thesis are to be interpreted as evidence-based and realistic conceptual systems which are not necessarily fully tested operational systems.

5.6 Recommendations for future research

This topic could be followed up in several other ways in future research.

First, a testing of the conceptual framework proposed in this thesis in real PV recycling operations in Finland is needed. A pilot study might take place on the real collection and sorting system and the various indicators, such as lead time, waiting time, sorting accuracy, material recovery rate and cost per tonne could be measured prior to and after improvements to the lean systems are made.

Secondly, the study could be replicated in another Nordic country, e.g., Sweden or Norway. Such a comparison may indicate some ideas on how the geographical conditions, climate, regulations and the market size influence the design of lean and circular PV recycling.

Third, there could be further detailed cost-benefit analysis performed on lean tools such as VSM, 6S and kaizen. This would facilitate enterprises and policy makers' understanding of the economic usefulness of these tools in the small-volume and long-distance supply chains of reverse logistics, such as Finland.

Fourth, future research will be able to explore ways in which digital tools can enhance PV waste management systems. The real-time panel tracking systems and Digital Product Passports could, for instance, facilitate value stream mapping, waste flow monitoring and optimisation based on data throughout the PV recycling value chain in Finland.

5.7 Final conclusion

Based on this thesis, it can be concluded that lean management principles, in particular value stream mapping, 6S including Safety and kaizen, can be used for enhancing operational efficiency as well as solar panel recycling sustainability in both Finnish solar panel recycling systems.

The study established the conceptual framework, measurable indicators and practical Finnish examples related to PV end-of-life management, by integrating the lean management and circular economy thinking.

The study also extended beyond the level of high-level policy targets and emphasized more on operational design challenges, like transport routes, waiting times, sorting accuracy, material recovery, workplace organisation, etc.

The concept is not yet tested in actual recycling plants, but the framework is helpful to start with for the policy makers, recycling companies, logistics operators who wish to establish more efficient and sustainable PV recycling solutions in Finland.

The volumes of PV waste will grow in the future in line with the increasing PV energy capacity in Finland and in Europe. For this reason, it might become possible to support the carbon neutrality and circular economy objectives in more practical way by initiating the lean and circular PV recycling systems in the early planning and development phase which may help to mitigate future PV waste issues.

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Appendix

Appendix A

Number of Article	Name of Author	Published Year	Geographical focus	Method used	Key points used in thesis	Match with Finland context	Quality score (1-3)
1.	(Wei et al., 2025a)	2025	International study	Literature review method	Study focusses on high value material recovery and recycling solar panel	Medium concepts applied	3
2	(Piedrahita et al., 2025)	2025	International study	Literature review	Study focuses on PV waste management challenges including circular economy, policy and regulation.	Medium concepts applied	3
3	(Iakovou et al., 2024)	2024	International study	Supply chain system analysis.	Study focus on end of life solar panel reverse supply chain and reverse logistics	Medium concepts applied	3

4	(Franz & Piringer, 2020)	2020	Europe	Statistical analysis and literature review	Study focus on end-of-life management, land used, recycling challenges for free field photovoltaic systems in the Europe.	High for the Finnish geography and logistics	3
5	(Marinna et al., 2025)	2025	International Base	Decision framework and case study basics	Study focus on the circular economy and the performance evaluation.	High for Finland circular approach.	3
6	(Ndzibah, Cruz, et al., 2022)	2022	Developing economics base	Case study basic including survey, interview, meeting references.	Study focus on end of life analysis of the PV panel by stakeholders management .	Low but can be useful for circular pathways.	3
7	(Lindahl, 2024)	2024	Sweden	Qualitative data analysis in production company.	Study focus on the circular production operations management developing Integrated Circularity Management Systems (ICMS) framework.	Medium used for industrial circular operations	3

8	(El Hafiane et al., 2025)	2025	International base	Systematic literature review used PRISM 2020 Guideline.	Study focus on the lean construction support circular goal but operational application seems weak.	Hight for Finland sustainable construction and circular goal.	3
9	(Teixeira et al., 2025)	2025a	Global Base	Systematic literature review used PRISM portal.	Focus on waste reduction, resources efficiency and sustainable performance improvement	High and can used directly to support the thesis framework.	3
10	(González-Reséndiz et al., 2018)	2018	Mexico (Logistics-case)	Used response surface methodology (RSM)	Study focus on optimization of logistics and distribution cost in supply chain operations.	Medium used for lean logistics concepts	3
11	(Preet & Smith, 2024)	2024	International Base	Comprehensive systematic literature review	Focus on Silicon-based PV recycling technology, system factors (transport, policy) matter as much as technology.	High and used for system view and supports lean link	3

12	(Luu et al., 2025)	2025	Italy (Italian solar photovoltaic sector)	Used quantitative material flow and impact analysis.	Focus on material demand and PV end-of-life contributions to circular economy and recycling benefits depend on system conditions.	Match circular economy and low carbon energy transition goals.	3
13	(Sasso et al., 2025)	2025	Global literature review on manufacturing sector	Systematic literature review and used thematic synthesis.	Focus on synergies between lean management and circular economy and lean affects sustainability through process changes.	Medium used for the conceptual integration	3
14	(Ghaithan et al., 2023)	2023	Manufacturing (generic)	Empirical survey	Study focus on impact of lean, Industry 4.0, and circular economy on sustainability performance.	Low , not PV-specific	3
15	(Iseri et al., 2025a)	2025	International Base	Used multi-objective optimization framework	Study focus on Circular economy systems engineering framework for PV waste for renewable energy systems.	Medium used in conceptual for Finland	3

16	(Zhou & Li, 2025)	2025	International (BIPV) base	Used multi-objective optimization modelling	Study focus on optimization of reverse logistics network and closed loop supply chain design for PV building integration.	Medium used for network design for Finland.	3
17	(Oreski et al., 2026) (IEA-PVPS)	2026	International base	Policy and technical report.	Study focus on second-life PV modules require qualification, testing, infrastructure, and regulation.	High used for informs Finnish reuse planning	Grey
18	Europa (Ecodesign)	2024b	EU Basics	Regulation Report	Study on Ecodesign for Sustainable Products Regulation and Digital Product Passport for traceability.	High used EU policy for Finland	Grey
19	Europa (waste projection)	2025b	EU Basics	Technical report	Study shows 21-35 million tons PV waste by 2050 and EU-27 projections.	High used for Finnish estimates	Grey
20	Europa (implementation)	2026	EU Basics	Policy update	Study on Implementing Ecodesign for Sustainable Products Regulation.	Medium for making policy.	Grey

21	Energy Authority	2024	Finland	Finland National report	Study shows Solar capacity (1,200 MW) and electricity market in Finland.	High as it directly Finnish context.	Grey
22	Ym (Climate Act) (Ministry of the Environment ,2021	2026	Finland	National report	Finland's carbon neutrality target for 2035.	High as related to Finnish policy	Grey
23	(Nieto Morone et al., 2025)	2025	EU Base	Used qualitative data analysis of PV waste mass generation.	Study on forecasting PV waste generation projections in EU, country level differences in PV end of life waste volumes.	High used for EU waste projection.	3
24	Pvps (IEA)	2012	International Base	Trend report	Study focus on trends in PV applications and baseline for waste growth.	Low used for background.	Grey
25	(Nussbaumer-Streit et al., 2025)	2025	Global overview	Global overview evidence synthesis type	Study on types of evidence synthesis and systematic reviews.	Low used for method section.	2
26	(Page et al., 2021a)	2021	International Base	Systematic literature Guideline	Study focus on PRISMA 2020 updated statement for systematic reviews	Low used for methodology	Grey

27	(Gusenbauer & Gauster, 2025)	2025	International Base	Methodological guide	Study Step-by-step guide for literature search in systematic reviews.	Low used for methodology	2
28	(Thaivalappil et al., 2018)	2018	Food sector	Thematic synthesis	Study Systematic review and thematic synthesis methodology.	Low – method only and thematic analysis.	2
29	(Goldenberg et al., 2026)	2026	International	Thematic synthesis	Study on thematic synthesis of experiences and perceptions.	Low – method only and thematic analysis.	2
30	(Seuring et al., 2021)	2019	International	Textbook	Research Onion methodology framework.	Low – general method	2
31	(Agrawal et al., 2024)	2024	International Base	Methodological review	Study focus on PRISMA checklist guidance for systematic reviews.	Low used for general methodology.	2
32	(Chen et al., 2023)	2025	International	Methodological review	Focus on quality assessment in systematic reviews using PRISMA and AMSTAR.	Low	2
33	(Dhingra & Jaiswal, 2025)	2025	International Base	Systematic literature Guideline using PRISMA framework.	Study on determinants of digital transformation; TCCM framework.	Low	2

34	(Elsman et al., 2024)	2024	International Base	Guideline development study.	Study on PRISMA-COSMIN for outcome measurement instruments.	Low	2
35	(Harari et al., 2020)	2020	International Base	Methodological review of systematic review search strategies.	Study base on Literature searches in systematic reviews and recommendations.	Low	2
36	(Inácio et al., 2025)	2025	International	Systematic literature review	Focus on Ecosystem accounting implementation.	Low	2
37	(Veroniki et al., 2025)	2025	International	Scoping review	Updating PRISMA for network meta-analysis.	Low	2
38	(Al-Omari et al., 2025)	2025	International	Technical review	Focus on role of automation in PV panel performance; limited end-of-life focus.	Low	2
39	(Andersen, 2022)	2022	Europe	Comparative study	Focus on WEEE directive variations across EU; manufacturer perspectives.	Medium – EU policy context for Finland	3
40	(Bošnjaković et al., 2023)	2023	Europe	Review	Focus on End-of-life readiness in Europe, policy	Medium used for EU background	3

					and infra-structure gaps.		
41	(Brussa, 2025)	2025	International	Book chapter	Photovoltaic panel material composition and recycling challenges.	Low	2
42	(Carmona Marques et al., 2026)	2026	Cross-sector	Conceptual framework	Focus on Integration of circular economy and lean management strategies.	Low used for conceptual only	3
43	(Diez-Suarez et al., 2024)	2024	Mediterranean region	Literature Review	Focus on recycling silicon-based PV modules; technical challenges.	Low – not Nordic	3
44	(Iturralde Carrera et al., 2025)	2025	International	Systematic Literature review used PRISMA Methodology	Focus on efficiency and sustainability factors in PV systems.	Low	2
45	(Kastanaki & Giannis, 2022)	2022	Europe	Qualitative assessment and forecasting analysis	Focus on PV waste recycling potential in EU decarbonization.	Medium – EU context	3
46	(Martínez et al., 2024)	2024	International	Review Study	Focus on Technological advancement in PV recycling.	Low – technical focus	3

47	(Nain & Anctil, 2024)	2024	EU vs. US	Comparative policy	Focus Regulatory approaches to PV waste management; EU vs. US.	Medium – EU policy background	3
48	(Nascimento et al., 2022)	2022	Recycling (3D printing)	Case study	Focus on Circular value stream mapping 4.0.	Low – different recycling context	3
49	(Padhamnath, 2025)	2025	International	Study Review	Focus on recovery and recycling of polymers from end-of-life silicon PV modules.	Low – technical focus	2
50	(Prashar & Chaudhuri, 2025)	2025	Manufacturing	Empirical study	Focus on Digitalization for circular economy and operational excellence.	Low – not PV-specific	3
51	(Rodrigues et al., 2026)	2026	International	Review	Focus on PV module recovery, recycling, and circular economy perspectives.	Medium – general	3
52	(Samimi & Hosseinlaghab, 2025)	2025	International	Study Review	Focus on electromagnetic monitoring for sustainability in PV lifecycle.	Low	2

53	(Wang et al., 2024)	2024	China vs. EU	Comparative analysis	Focus on Insights for China from EU management of end-of-life PV modules.	Medium – EU policy comparison	3

Appendix B

Appendix B				
Number of study	Name of Author	Published Year	Quality score	Reason for point score
1	(Agrawal et al., 2024)	2024	2	Methodological, not PV-specific
2	(Al-Omari et al., 2025)	2025	2	Technical, limited end-of-life
3	(Andersen, 2022)	2022	3	Clear comparative method, EU policy relevance
4	(Oreski et al., 2026) (IEA-PVPS)	2026	Grey	High-quality grey literature, used for context
5	(Bošnjaković et al., 2023)	2023	3	Good review with policy relevance
6	(Brussa, 2025)	2025	2	General chapter, limited depth
7	(Carmona Marques et al., 2026)	2026	3	Strong conceptual framework for lean-CE
8	(Chen et al., 2023)	2025	2	Methodological, not PV-specific
9	(Dhingra & Jaiswal, 2025)	2025	2	Methodological

10	(Diez-Suarez et al., 2024)	2024	3	Good technical review, but Mediterranean focus
11	(El Hafiane et al., 2025)	2025	3	Strong SLR on lean-CE integration
12	(Elsman et al., 2024)	2024	2	Methodological
13	Energy Authority	2024	Grey	National data, essential for Finland
14	Europa (Ecodesign)	2024b	Grey	Policy document, high relevance
15	Europa (DPP consultation)	2025a	Grey	Policy background
16	Europa (waste projection)	2025b	Grey	Core waste volume data
17	Europa (implementation)	2026	Grey	Policy update
18	(Franz & Piringer, 2020)	2020	3	Strong Finland-specific context, empirical
19	(Ghaithan et al., 2023)	2023	3	Good empirical study, but manufacturing not PV
20	(González-Reséndiz et al., 2018)	2018	3	Good lean logistics case study
21	(Gusenbauer & Gauster, 2025)	2025	2	Methodological
22	(Harari et al., 2020)	2020	2	Methodological
23	(Iseri et al., 2025b)	2024	3	High-quality reverse logistics model, strong relevance

24	(Inácio et al., 2025)	2025	2	Not PV-specific
25	(Iseri et al., 2025b)	2025	3	Strong CE systems engineering
26	(Iturralde Carrera et al., 2025)	2025	2	General review
27	(Kastanaki & Giannis, 2022)	2022	3	Good EU-level assessment
28	(Lindahl, 2024)	2024	3	Strong CE operations framework
29	(Luu et al., 2025)	2025	3	Good case study, transferable methods
30	(Marinna et al., 2025)	2025	3	Excellent reuse framework, high relevance
31	(Martínez et al., 2024)	2024	3	Good technical review
32	(Nain & Anctil, 2024)	2024	3	Good policy comparison
33	(Nascimento et al., 2022)	2022	3	Circular VSM, different context but method useful
34	(Ndzibah, Andrea Pinilla-De La Cruz, et al., 2022)	2022	3	Good circular pathways, developing economy context
35	(Nieto Morone et al., 2025)	2025	3	Strong projection study, includes Finland
36	(Nussbaumer-Streit et al., 2025)	2025	2	Methodological

37	(Padhamnath, 2025)	2025	2	Technical review, limited operations
38	(Page et al., 2020)	2020	Grey	PRISMA guideline
39	(Page et al., 2021b)	2021	Grey	PRISMA guideline
40	(Piedrahita et al., 2025)	2025	3	Good review of PV waste challenges
41	(Prashar & Chaudhuri, 2025)	2025	3	Good empirical study, manufacturing focus
42	(Preet & Smith, 2024)	2024	3	Excellent comprehensive review, system view
43	Pvps (IEA)	2012	Grey	Historical baseline
44	(Rodrigues et al., 2026)	2026	3	Good recent review
45	(Samimi & Hosseinlaghab, 2025)	2025	2	Specialised, not operational
46	(Sasso et al., 2025)	2025	3	Strong lean-CE integration
47	(Teixeira et al., 2025)	2025a	3	Directly supports framework, strong conceptual
48	(Thaivalappil et al., 2018)	2018	2	Methodological, food sector
49	(Veroniki et al., 2025)	2025	2	Methodological
50	(Wang et al., 2024)	2024	3	Good comparative policy analysis

51	(Wei et al., 2025b)	2025	3	Strong technical review with operational implications
52	(Zhou & Li, 2025)	2025	3	Good network optimization, transferable to Finland