Exploring Niche Strategies for the Circular Innovation of PV Panels in India

Sustainable Energy Technology

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Abstract

The potential of 748 GW of solar capacity presents a significant challenge: the effective end-of-life (EOL) disposal of photovoltaic (PV) panels. Failure to manage this process could result in substantial environmental impacts and resource depletion. This thesis, titled ”Exploring Niche Strategies for the Circular Innovation of Photovoltaic (PV) Panels in India,” seeks to analyze the key factors that either promote or hinder circular innovation within the Indian PV industry. The study also aims to propose niche strategies to overcome these barriers. To systematically address the challenges associated with recycling EOL PV panels, this research applies and adapts the Technological Innovation System framework to circular innovation of PV panels in India. Through literature review and in-depth interviews with key industry stakeholders, the study identifies the primary drivers and barriers to circular innovation of PV panels in India. The thesis advocates for niche strategies to overcome these barriers, providing valuable insights for industry players and researchers alike.

Summary

India's rapidly expanding solar energy sector faces a significant challenge: managing the end-of-life (EOL) photovoltaic (PV) panels that will inevitably result from this growth. While the exponential increase in PV panel installations is essential for increasing energy demand, it also brings environmental and logistical challenges due to the current lack of infrastructure and processes for recycling these panels. This research explores niche strategies for circular innovation in India's solar industry, focusing on key questions: What are the drivers, barriers, and niche strategies for PV panel circularity in India? How to adapt the Technological Innovation System (TIS) framework for circular innovation? By addressing these questions, the study aims to identify the most effective strategies for implementing circular practices and managing PV waste in India.

The study begins by examining the concept of the circular economy. In the context of PV panels, circular innovation involves developing systems and strategies for recycling materials, thereby reducing environmental impact and conserving resources. The research initially utilized the TIS framework developed by Dr. Ortt and Dr. Kamp as the basis for analysis. However, Raghav Shankar and Jules Engelen, former TU Delft students, contributed to the creation of a combined TIS framework specifically tailored to address the unique challenges of circular innovation. By integrating their frameworks, the study aimed to capture all aspects of circular innovation that individual adaptations might have overlooked. This combined framework guided the formulation of questions and discussion topics for semi-structured interviews with Indian solar industry professionals, ensuring a thorough exploration of the drivers and barriers to circular innovation.

Through a comprehensive literature review and in-depth interviews with industry professionals, the research identified key drivers and barriers to circular innovation in India, as highlighted in Figure 1. To address the identified barriers, the study proposed several niche strategies, developed based on the barriers and their influencing conditions, ensuring a targeted and effective approach. The combined TIS framework for circular innovation was adapted to better align with the specific needs and challenges of India's solar industry.

Drivers	Barrier
Increasing Energy Demands	Lack of Regulations, Policies, Incentives
Augmentation of Solar Capacity	Degradation of the quality of recovered silicon
Premature PV Waste Generation	High initial setup and reverse logistics costs
High Dependence on Imports	Lack of Formal Recycling Facilities
Availability and Affordability of Materials	Economic viability of recycling certain materials
Projected EOL PV Waste	Lack of government leadership & initiatives
Hazardous Materials in PV Waste	Lack of Accountability & Coordination,
Critical Metals Supply Crunch	Product Stewardship Approaches (EPR)
Regulatory Gaps	PV Waste Management Systems (Collection, Sorting)
Need for Regulations and Incentives	MNRE Blueprint

Figure 1: Drivers and Barriers

The findings of this study have significant implications for both policymakers and industry stakeholders. For policymakers, there is an urgent need to develop and implement regulatory frameworks that support circular innovation. These frameworks should include financial incentives, clear guidelines for recycling and waste management, and a focus on their successful implementation. For industry stakeholders, the proposed niche strategies offer solutions for overcoming the barriers to circularity, fostering a more sustainable and efficient solar industry in India.

However, the research's regulatory analysis is based on existing literature and may become outdated as practices evolve. Additionally, the scope of the interviews was limited, involving a small number of industry experts, and lacked substantial input from government officials and the informal sector, potentially limiting the comprehensiveness of the findings. The study also faced limitations such as a geographic focus restricted to India, challenges in adapting a European-based framework (the TIS) to the Indian context, and the potential oversimplification of the complex PV recycling ecosystem. The lack of integration of the informal sector and incomplete data on PV waste generation and recycling rates in India further underscore areas that require additional research and attention.

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Introduction

With the arrival of the industrial ages, humans learned how to exploit sunlight as a valuable source of energy. India possesses a vast potential for harnessing solar energy. India's geographical area receives approximately five trillion kilowatt-hours of incident energy annually. Solar power has the additional benefit of decentralised power production, allowing for rapid and efficient scalability of solar power capacity within a short timeframe (New and Renewable Energy, 2023a).

The primary benefits of decentralised off-grid systems and applications at low temperatures are to provide a varied range of energy services, including electricity, heat, and cooling, in both rural and urban areas. Solar energy is considered the most reliable kind of energy due to its abundant availability. In theory, a country can efficiently fulfil all its energy requirements by harnessing a small portion of the overall solar energy available. Therefore at the moment, solar energy is of great importance in the energy landscape of India. Decentralised and distributed solar applications have shown to be highly effective for the majority of individuals residing in rural India. These applications effectively address their fundamental requirements such as cooking, lighting, and other energy-dependent needs, while adhering to environmentally friendly norms. The National Institute of Solar Energy (NISE) has calculated that the solar potential of the country is approximately 748 GW, taking into account various factors. This calculation takes into account the allocation of 3% of the total wasteland area for the installation of photovoltaic modules (New and Renewable Energy, 2023a).

The National Action Plan on Climate Change announced the National Solar Mission and delineated its significance. According to the (New and Renewable Energy, 2023a), India's solar PV installation estimates surpassed those of the REN21 Global Status Report 2023 and IRENA Renewable Capacity Statistics 2023. The report indicated that India would become the fifth-largest global installer of solar energy. The data also reveals a significant increase in the installed capacity of hydropower and other renewable sources, reaching 179.322 GW of total renewable energy capacity. Among these sources, solar power accounts for 67.07 GW, representing slightly more than 37% of the total installed capacity. India aims to reduce its economy's carbon intensity by at least 45% by the end of the decade (India, 2023).

This nationally decided objective aims to decrease the energy intensity in the gross domestic product for each unit of greenhouse gas emissions by one-third. The government aims to achieve a total installed capacity of 500 gigawatts for renewable energy by the year 2030. India has granted formal authorisation for 57 solar parks, which have a combined capacity of 39.28 GW (India, 2023). One of the objectives of the National Action Plan on Climate Change is to highlight the favourable climate conditions in tropical India, where there is enough sunlight for several months of the year. This makes solar energy a promising future source of energy. Furthermore, the advantage of decentralising energy provides increased autonomy and authority to individuals within the local community, granting them control over the circumstances (New and Renewable Energy, 2023b).

However, considering the projected volume of PV e-waste is much higher than other e-waste and consists of enormous quantities of basic, hazardous, and critical materials, very little research has been conducted in the context of resource recovery from end-of-life (EOL) PV or practices of recycling, reusing, and remanufacturing. Installed PV modules worldwide provide a lifetime of useful service before becoming end-of-life (EoL) items. The typical life of a solar panel is 25 to 30 years, but this can be lower as well due to several factors; hence, this level of deployment will create vast amounts of waste in India within no time (Gautam, Shankar, and Vrat, 2021).

1.1. Problem Statement

India now has a solar energy capacity of slightly over 67 GW, and aims to reach a capacity of 748 GW, which may establish the country as a global leader in solar energy installations. In the future, the disposal of photovoltaic waste will provide an additional difficulty for the country. Not only does this practice deplete valuable resources, but it also simultaneously endangers human health and the environment. The TIS framework takes a comprehensive picture of this transition, considering the interplay between technology, institutions, and society. In India, the circular economy approach for managing PV waste is implemented using this framework to effectively address any obstacles.

1.1.1. Research Questions

This thesis aims to explore niche strategies for the circular innovation of end-of-life (EOL) photovoltaic (PV) panels, with a prime focus on India and recycling of PV panels. Only by addressing the following sub-questions will we be able to adequately answer the overarching purpose, thereby providing a systematic approach to analyzing the matter under discussion.

Main Research Question

What are the key drivers and barriers to circular innovation for EOL PV panels in India, and how can the application of niche strategies help overcome these challenges?

Sub Research Questions

1. **What are the drivers to circularity of PV in India?**
2. **What are the barriers to circularity of PV in India?**
3. **Which niche strategies would be best suited for circularity of PV in India?**
4. **How to adapt the framework for the case of circular innovation in India?**

Research Methods

Following menthods will be used to answer the research questions:

1. What are the drivers to circularity of PV in India?
   Literature Review: Examine existing studies, reports, and academic papers on the circularity of photovoltaics in India to identify documented barriers.
   Interviews with professionals: Conduct interviews with key stakeholders in the PV industry.
2. What are the barriers to circularity of PV in India?
   Literature Review: Examine existing studies, reports, and academic papers on the circularity of photovoltaics in India to identify documented barriers.
   Interviews with professionals: Conduct interviews with key stakeholders in the PV industry.
3. Which niche strategies would be suited for circularity of PV in India?
   Stakeholder analysis: Identifying key actors involved in the Indian PV industry and their roles, interests, and relationships.
   Literature Review: Examine existing studies, reports, and academic papers on

the circularity of photovoltaics in India to identify documented barriers.
Interviews with professionals: Conduct interviews with key stakeholders in the PV industry.

4. How to adapt the framework for the case of circular innovation in India?
   Literature Review: Examine existing studies, reports, and academic papers on the circularity in India to identify documented barriers.
   Interviews with professionals: Conduct interviews with key stakeholders in the PV industry.

1.2. Research Flow Diagram

A research flow diagram like in 1.1 is one of the most critical segments within a thesis because it allows for a vivid and transparent visual representation of the entire process of conducting the research. This explains, for one, the logical sequence of activities involved in research from the identification of the research problem up to the analysis and interpretation of data. Additionally, this graphic aid contributes to the overall coherence of the study presentation, going beyond simply organizing the methods section. The flow diagram establishes the reproduction effect, enabling other researchers to replicate the research and confirm the findings. It also shows methodological rigor, an essential quality of academic research.

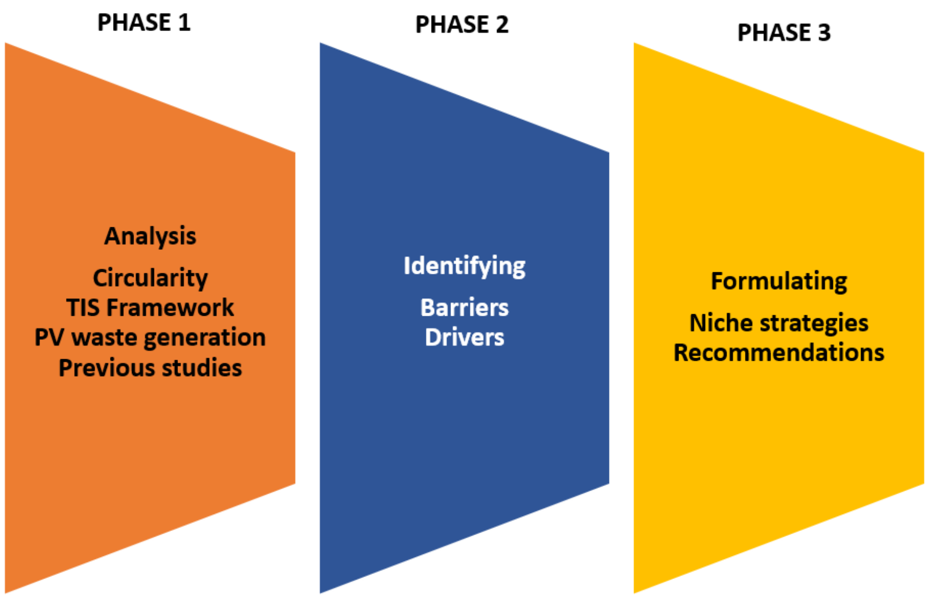

Figure 1.1: Research Flow Diagram

2 Literature Review

Chapter 2 presents a comprehensive exploration of circular innovation in the context of photovoltaic (PV) panels, focusing particularly on India's approach to solar waste management. The chapter begins by introducing the concept of the circular economy (CE) and contrasting it with the traditional linear economic model. CE emphasizes waste reduction through practices such as reuse, repair, remanufacturing, and recycling. It also discusses the theoretical and practical challenges associated with implementing these circular principles, including the cultural shifts required within companies to operationalise these objectives.

The chapter then delves into the Dr. J. Roland Ortt and Dr. Linda M. Kamp's Technological Innovation Systems (TIS) framework, which is essential for analyzing the initial circumstances surrounding innovation and creating effective niche introduction strategies. The discussion includes general niche strategies and integrates insights from Jules Engelen and Raghav Shankar's theses, which apply the TIS framework to circular innovations, providing valuable perspectives for its implementation.

Section 2.3 devotes a significant portion to the current state of solar waste management in India. It emphasizes the challenges posed by the rapid increase in solar waste and the inadequacies of existing recycling facilities. Subsection 2.3.3 underscores the environmental risks associated with improper disposal of PV panels and emphasises the urgent need for a circular approach to manage the end-of-life (EoL) stage of PV modules effectively.

Section 2.4 provides a global perspective on PV waste trends, categorising different countries' practices in managing solar waste and detailing the risks posed by the materials used in PV panels. This global view offers insights into best international practices, which could guide the development of an appropriate strategy for India's solar waste management. In addition, the chapter explores the processes involved in recycling PV panels in Section 2.4.3, focusing on module deconstruction, crystalline silicon recycling, and the treatment of other components such as backsheet polymers and encapsulants. It discusses advanced recycling technologies and their associated challenges, providing a comprehensive overview of current recycling methods.

Finally, Section 2.6 examines the key drivers and barriers to PV recycling in India, setting the stage for subsequent research and practical implementation in the following chapters. This chapter establishes a solid foundation for understanding the landscape of circular innovation in PV panels, which is crucial for developing sustainable solutions in the solar industry. In Chapter 2, we look in depth at both the theoretical frameworks and practical challenges of circular innovation in PV panels. This sets the stage for the research and strategies that will be talked about in the following chapters.

2.1. Circular Economy

The traditional model of "take-make-dispose" economics has remained the mainstay for most industries worldwide and accrued an appreciable share of environmental degradation, resource depletion, and waste accumulation. In view of rising global challenges, including climate change, resource scarcity, and environmental pollution, the linear model of economics is fast becoming unsustainable. In its place, the concept of a circular economy provides a very transformable solution that emphasises restoration, regeneration, and the sustainable management of resources (Ellen MacArthur Foundation, 2012).

A circular economy model provides a more sustainable alternative to the traditional take-make-dispose model of economies. It takes into account the reduction of waste generation and encourages significant innovations in materials, products, systems, and business models. A circular economy closely promotes the use of renewable energy sources, the elimination of hazardous chemicals, and the avoidance of waste production at all times. This concept involves preserving the environment while ensuring overall well-being by monitoring and enhancing economic growth at the individual, organisational, and national levels. According to the Ellen MacArthur Foundation, one of the world's leading authorities in the circular economy, an economic system decoupled from finite resource consumption for growth. The corpus of work the foundation has put together demonstrates that practices in circular economies could create an economic opportunity that makes business sense, propels innovation, and finally ensures social fairness by reducing their ecological impacts (Ellen MacArthur Foundation, 2012).

In recent years, there have been a number of research and policy activities on CE, mostly motivated by its potential to increase economic value and promote social justice. However, current efforts by scholars to probe into the concept of the effect of CE on business remain relatively undefined. These studies hint that, although circular practices have significant benefits, they are not free of management challenges. Indeed, drastic changes to operations and culture may be necessary for organisations to manage their products properly over the whole lifecycle (Barros et al., 2021).

The transition to a circular economy holds many promises, but it is not without challenges. Fully closed-loop systems are hard to realize. Geissdoerfer et al., 2017 offer a heuristic definition: ”The circular economy is an industrial system that simultaneously degrades and regenerates within a continuous process of closing loops, while simultaneously minimizing energy and resource waste.” However, it should be noted that this approach is susceptible to potential shortcomings. Moreover, the diffusion of sustainable modes of consumption and production will face numerous obstacles, ranging from large upfront investments over complex supply chains to infrastructure lock-ins and consumer apathy (Preston, 2012, Böttcher and Müller, 2015).

This is why it is crucial to gain a deeper understanding of the questions surrounding CE, especially the emerging concepts. While traditional innovations concentrate on developing mass-produced goods through research and development, they often fail to explore the potential diffusion of innovation itself. ”Circular innovation” encompasses all forms of innovation, even if they are difficult to reach. On the other hand, it provides substantial returns for a sustainable and resilient future (Suchek et al., 2021).

In this context, we should emphasise some key barriers to circular innovation, including inadequate information and financial resources for the implementation of circular economy projects, unsatisfactory regulations, and a lack of relevant knowledge and competencies. There are practical challenges that companies face in implementing effective circular approaches (Pieroni, McAloone, and Pigosso, 2021, Corvellec, Stowell, and Johansson, 2022). Accordingly, it will be of special interest to tease out how research can help in identifying major characteristics that foster or impede circular innovation, more specifically with respect to niche strategies.

2.1.1. Circular Innovation

What has brought circular innovation to the forefront of shifting towards a more sustainable future is its central driving force in the shift from linear to a circular economy.

Circular innovation refers to the development of new products, services, business models, and processes that reduce waste and resource consumption while also increasing the value of products and materials throughout their life cycles (De Jesus and Mendonça, 2018).

There are mainly two types of circular innovations: incremental and radical. Incremental ones deal with continuous, small changes to existing products or processes, whereas radical ones deal with fundamental change—a complete redesign of products and services. History has always shown that technological and social innovations have been the pivot of major economic transformations, from the Industrial Revolution to the now common notion of tomorrow's Circular Revolution (Dedehayir and Steinert, 2016, Hermann and Wigger, 2017, Carrillo-Hermosilla, Del Río, and Könnölä, 2010, De Jesus and Mendonça, 2018).

Furthermore, these circular innovations not only provide significant economic and far-reaching social benefits, but they also aid in the fight against environmental challenges. Such wealth also comes with a number of potential barriers to circular innovations, including the inaccessibility of information and financial resources, a lack of regulatory support, and a lack of knowledge and skills within business. Another challenge lies in enhancing consumer behavior, transforming business practices, and elevating societal norms, all necessary for a transition from a linear economy (Hekkert et al., 2007, Geels, 2002).

In these respects, TIS and niche strategy frameworks contribute meaningfully to the surmounting of barriers to the diffusion of circular innovations. Companies and policy-makers can accelerate the transition to a circular economy by strategically managing the processes involved in the introduction and scaling of circular innovations, thereby laying the groundwork for the creation of a sustainable and resilient future.

2.2. Technological Innovation Systems (TIS) Framework

J. Roland Ortt and Linda M. Kamp developed the framework. It specifically develops the challenging conditions that most firms go through while attempting to realise far-reaching innovative technological developments. This connects the socio-technical systems theory to the literature on innovation studies and strategic management. This becomes particularly valuable in the context of circular innovation (Ortt and Kamp, 2022).

It not only gives an insight into which of the key building blocks and the influencing conditions contribute favourably to the success of such innovations but also provides the stakeholders with the constituting elements of a technological system so that appropriate strategies can be taken to overcome the barriers and come up with widespread adoption of circular practices (Ortt and Kamp, 2022).

The TIS framwork is based on seven key building blocks, each of which is necessary for the success of technological innovations. When a building block is absent, incomplete, or incompatible, it impacts the overall acceptance of innovation processes. It allows for the early examination of novel situations within the TIS. Secondly, it outlines the scope, scale, and types of various niche introduction strategies that can be developed within the TIS (Ortt and Kamp, 2022).

In addition to considering the building blocks for innovations, it also considers the influencing conditions, which have the potential to either promote or hinder the development of an innovation. How these influencing conditions interact with the building blocks then shapes the pathways for technological development (Ortt and Kamp, 2022).

2.2.1. Understanding the TIS Framework

The TIS framework, as developed by Ortt and Kamp, integrates ideas from socio-technical systems theory with innovation and strategic management. It consists of seven building blocks and is influenced by seven conditions that impact the adoption and diffusion of new technologies. These building blocks and influencing conditions are shown in 2.1

Building Blocks	Influencing Conditions
Product performance and quality	Knowledge and awareness of technology
Product price	Knowledge and awareness of application and market
Production system	Natural, human and financial resources
Complementary products and services	Competition
Network formation and coordination	Macro-economic and strategic aspects
Customers	Socio-cultural aspects
Innovation-specific institutions	Accidents and events

Figure 2.1: TIS Framework: Building Blocks and Influencing Conditions by Ortt and Kamp, 2022

The TIS framework also emphasizes the importance of niche strategies in overcoming barriers to innovation, particularly for highly innovative technologies that face significant market entry challenges (Ortt and Kamp, 2022).

2.2.2. Niche Strategies

Niche strategies are central to the TIS framework, particularly when dealing with highly innovative technologies that face significant barriers to market entry. According to Ortt and Kamp, 2022, various combinations of building blocks and influencing conditions give rise to distinct niche strategies that can be employed to overcome specific challenges.

Ortt, 2010 research identified ten general niche strategies that have been successfully used in various historical contexts to introduce high-tech products. These strategies are shown in 2.2

Generic Niche Strategies	Description
Demo, experiment and develop niche strategy	In situations where there is a limited understanding of the technology, leading to restricted product availability and limited functionality, this strategy can be employed. This approach involves showcasing the product to the public to address concerns about its limited performance quality. Experimental facilitation enables ongoing product development, where enhancements can be made to improve functionality and overall quality.
Top niche strategy	A limited understanding of the technology hinders the product's availability at a reasonable cost, and issues with the production system. To overcome these challenges, a top niche strategy can be implemented, offering customized, small-scale production for a specific high-end market segment. Alternatively, a skimming strategy can be employed to prioritize supplying a unique product to the top niche customers.
Subsidized niche strategy	Lack of knowledge and the resources required to develop the product predominantly affects the product price. This strategy can be adopted in such a way that the product can be subsidized to a particular segment of customers.
Redesign niche strategy	This strategy facilitates the introduction of a simplified product version produced with available knowledge and fewer resources to achieve a more affordable price. This strategy can also be adapted in such a way that it can be deployed in the areas where institutional aspects are more supportive, and the customers and the suppliers have the least resistance.
Dedicated system or standalone niche strategy	This strategy involves using a product independently or creating a specialized system of complementary products and services, such as a local network, especially when a broader infrastructure is not accessible.
Hybridization or adaptor niche strategy	This involves utilizing the new product alongside the existing product, ensuring the reuse of complementary products and services. Another option is to provide an adaptor or converter to ensure that the new product and existing complementary products and services are compatible with each other.
Educate niche strategy	This involves focusing on transferring knowledge to suppliers, aiming to enhance their understanding of the product. Also, it emphasizes on implementing an educating and experimenting to increase customer knowledge and familiarity with the product.
Geographic niche strategy	Focusing on geographic areas where institutions, such as laws and rules, are more flexible or less stringent, allowing for easier implementation of the strategy and the resulting policies. Like redesign niche strategy, geographic strategy suggests moving the operations of a company to areas with availability of resources, potential suppliers and customers.
Lead user niche strategy	Identifying and engaging with innovators or lead users who are at the forefront of innovation. These individuals play a role in co-developing the product and providing valuable feedback, while the innovators are often open to experimenting with the product.
Explore multiple markets niche strategy	This strategy involves the exploration of various customer applications and stimulating customers to experiment and utilize the product in novel ways. This approach encourages exploration and creates opportunities for diverse and innovative applications.

Figure 2.2: Ten niche strategies to commercialize new high-tech products by Ortt, 2010

Approximately 80% of newly developed high-tech products are initially introduced in niche markets before they gain widespread acceptance in the mass market. By applying niche strategies, companies can create a supportive environment for the innovations, allowing them to gain traction and eventually scale to larger markets (Ortt, 2010).

2.2.3. Insights from Jules Engelen's Thesis

Jules Engelen's thesis explores the application of the TIS framework to the development and diffusion of circular innovations. Engelen's works are one-of-a-kind because they try to make sense of all the actions of different situations of circular innovations and the overall effects of a TIS that affect how innovations spread. He looks at the existing literature in a planned way to find the knowledge gaps in understanding how circular innovations spread. He then tries to fill these gaps by customising the development of a TIS framework that can be used in the circular economy (Engelen, 2023).

In terms of methodology, Engelen's study is rigorously based on most of the secondary literature in order to best build a robust theoretical base. First, he created a definition of circular innovation to fill the gap in previous literature. He uses insights from the literature to define the concept of a circular economy and CE-oriented innovations. Subsequently, he conducts a systematic literature review, scrutinizing ten articles to understand the ways and contexts in which various actors and factors impact the spread of circular innovation from a systems viewpoint. His study highlights the need for nuance in comprehending systemic factors like knowledge diffusion, institutional support, and market dynamics, and how these intertwine within each anchor phase of a TIS to impact the success of circular innovations (Engelen, 2023).

Engelen's work is particularly focused on tailoring the TIS framework to circular innovations. This represents a distinct form of technological innovation. The focus is on sustainability and resource efficiency. Engelen's analysis is particularly valuable in highlighting the specific TIS factors that require change to better support circular innovation. Reverse logistics and data infrastructure are two components that are quite absent from a traditional TIS framework but are very relevant for the success of circular innovation (Engelen, 2023).

Some future research avenues are suggested. One area of further research would be to extend the present analysis with a larger sample size, including more issues concerning higher circularity strategies and new circular business models. This would increase the external validity of the problems identified. Another way could be to explore the usability, completeness, and limitations of the TIS framework for application in organizations in the context of circular innovations through case studies or expert interviews. This way, one could detect probable issues not underlined in the literature and formulate recommendations for the framework's optimization (Engelen, 2023).

Below, you can see the specific indicators per building block in Figure 2.3 and per influencing conditions in Figure 2.4 . The last column in each table by the label of "Shortened" is just for making the content easier to use in tables in figures in this research. The last column was not specified by Jules instead it was I did to make it easier to use.

Building Blocks	Jules' (Detailed)	Jules' (Shortened)
Product Performance and Quality	- Functional quality of product made from recycled materials.	- Recycled quality
Product Price	- Recycled material price higher compared to virgin material price. - Price of circular versus linear product. - Overlong (hard to meet) ROI. - Hard to make a (profitable) business case.	- Price disparity - Circular vs linear price - Extended ROI - Business case challenge.
Production System	- Lack of economies of scale.	- Economies of scale
Complementary Products and Services		
Network Formation and Coordination	- Limited willingness to collaborate and sharing information. - Lack of network formation and organization. - Convincing partners to take circular approach. - Lack of collecting and recycling standards. - Lack of third parties to stimulate collaboration. - Resistance from (powerful) stakeholder in VC.	- Collaboration reluctance - Network formation - Convincing partners - Standards absent - Third-party absence - Stakeholder resistance
Customers	- Customer interest and acceptance. - Identifying and reaching customers.	- Customer acceptance - Reaching customers
Innovation-Specific Institutions	- Inconsistent legislation at different administrative levels: regional, national, and international. - Uncertainty in classifications of (raw) materials. - Lacking and unclear regulation. - Health and safety regulations of recyclables.	- Legislation inconsistency - Material classification - Regulation clarity - Health & safety
Reverse Logistics	- Lacking circular infrastructure. - Lacking reverse logistics. - Functional recycling systems.	- Circular infrastructure - Reverse logistics - Recycling systems

Figure 2.3: TIS Framework Building Blocks adaptations by Engelen, 2023

Influencing Conditions	Jules' (Detailed)	Shortened (Jules')
Knowledge and Awareness of Technology	- Product not designed for repair, refurbishment, disassembly, separation & recycling. - Unproven concept.	- Design limitations - Concept validation
Knowledge and Awareness of application and market	- Lack of knowledge (of CE or product/service performance). - Lack of sector knowledge by institutions. - Lack of data on impact of change.	- Knowledge gap - Sector knowledge - Impact data
Natural, Human and Financial Resources	- Limited volumes of (high quality) circular supply. - Access to capital (public and private). - Inconsistent flow of waste. - Product(ion) require high level of skill.	- Supply limitations - Capital access - Flow inconsistency - Skill requirements
Competition	- Competition for raw and recycled materials. - Variety of technologies available. - Regulations have relative higher strain on smaller firm.	- Material competition - Technology variety - Regulatory strain
Macro-Economic and Strategic Aspects	- Policies unsupportive for CE. - Tax schemes favour linear over circular. - Institutional preference for raw materials utilization. - Lack of CE criteria in public tenders.	- Policy support - Tax bias - Raw material bias - CE criteria absence
Socio-Cultural Aspects	- Unequal distribution of costs and benefits in value chain. - Counterproductive behaviour. - No interest in sustainable alternative. - Lacking enthusiasm for changing business operations. - Confused about circular process. - Potential reputation loss. - Limited possibilities of repair, refurbishment due to technological cycles.	- Value chain inequality - Counterproductive behaviour - Sustainable disinterest - Business inertia - Process confusion - Reputation risk - Repair limitations
Accidents and Events		
Data Infrastructure	- Difficulties tracking materials and components.	- Tracking difficulties

Figure 2.4: TIS Framework Influencing Conditions adaptations by Engelen, 2023

2.2.4. Insights from Raghav Shankar's Thesis

Raghav Shankar's thesis offered a unique and complementary perspective on the application of technological innovation systems within the context of Dutch high-tech firms. In contrast to Engelen, whose research is based on a more theoretical and literature-driven approach, Shankar anchors his analysis of the very topic on theoretical insights and empirical data acquired from the case studies of high-tech firms in their efforts towards circular innovation. That is, the mixed-method approach will allow Shankar to investigate the drivers and barriers of circular innovation (Shanker, 2023).

Shankar's thesis is outstanding due to its empirical rigour, which includes in-depth case studies of few Dutch high-tech companies that are leading the way in circular innovation. These cases gave Shankar a basis for testing the applicability of the TIS framework in practical situations and valuable insight into how one might adapt the framework to address certain challenges in companies working on circular economy issues. His work demonstrates the operational challenges and strategic decisions that firms must make while implementing circular innovations, including the practice-oriented perspective that usefully foregrounds Engelen's more theory-oriented approach (Shanker, 2023).

Shankar's thesis contributes immensely to understanding the dynamics of circular innovation for high-tech enterprises in the Netherlands. It provides useful information to both the business sector and policymakers about promoting the adaptation and integration of circular innovation. The outcome of the study lays emphasis on strategic alignment by the business entities with regulatory changes, collaborative networks, and an innovation-driven approach toward product design. However, the research has limited its scope to case studies. The geographical focus on Dutch firms further underscores this point. Therefore, further research could make it easier to extend to other contexts and industries. This thesis, therefore, provides an overall useful balance between empirical insights and the theoretical underpinning of potential ways to overcome barriers to circular innovation and to 'road-test' transformative change in the high-tech industry (Shanker, 2023).

Below, you can see the specific indicators per building block in Figure 2.5 and per influencing conditions in Figure 2.6 that were used to adapt the TIS framework for circular innovation by Raghav Shankar.

Building Blocks	Indicators (Raghav's)
Product Performance and Quality	- Design for circularity. - Resource Optimization. - Integrated PSS.
Product Price	- Long term feasibility. - Total cost of ownership.
Production System	- 9 (R)s capability. - Strong reverse logistics. - Flexibility & Adaptability.
Complementary Products and Services	- Collaboration. - Ecosystem of products/services. - Industry specific infrastructure.
Network Formation and Coordination	- Strong network. - Division of responsibility. - Shared goals.
Customers	- Awareness & knowledge. - Ownership preferences. - Resistance to change.
Innovation-Specific Institutions	- Standardisation. - General Consensus. - Emerging robust policies.

Figure 2.5: TIS Framework Building Blocks by Shanker, 2023

Influencing Conditions	Indicators (Raghav's)
Knowledge and Awareness of Technology	- Limited scope of circular products. - Large scale demonstration. - Uncertain returns.
Knowledge and Awareness of Application and Market	- Linear lock-ins. - Asymmetric information.
Natural, Human and Financial Resources	- Resource flow optimisation. - Leadership & team skills. - Availability of finances.
Competition	- Market positioning. - Conventional competition. - Value proposition.
Macro-Economic and Strategic Aspects	- Systemic perspective. - Economic conditions. - Conductive regulations.
Socio-Cultural Aspects	- Literacy & motivation. - Informed preferences. - Limited information & knowledge.
Accidents and Events	- Internal disruption. - Cascading effects. - Resilience.

Figure 2.6: TIS Framework Influencing Conditions adaptations by Shanker, 2023

2.2.5. Integrating Insights from Engelen and Shankar

Raghav Shankar and Julius Engelen's work focuses more on adapting the Technological Innovation System framework to understand and promote circular innovation. Their work primarily focuses on analyzing how various factors and actors can impact the development and diffusion of circular technologies. They approach this from a unique perspective (Shanker, 2023, Engelen, 2023).

Though different in approach, both studies are consistent with respect to the fact that collaborative networks, infrastructure developments, consumer activation, and niche strategies show promising ways to facilitate circular innovation. Integrating the adapted TIS frameworks by Shankar and Engelen allows for a comprehensive exploration of the best introduction strategies for circular innovation. This integrated framework reaps benefits from Shankar's detailed case study insights and Engelen's broad systemic analysis, thus providing a holistic understanding of the drivers and barriers to circular innovation. This combined framework, especially in the context of photovoltaic panels in India, can be particularly useful. The regulatory and policy environment in India for renewable energy and circular economy practices can be rather complex. Shankar's insights into the impact of upcoming regulations and Engelen's systematic review of policy-related barriers could potentially enhance businesses' ability to navigate and effectively utilize regulatory frameworks that support circular innovation. Circular innovation in the PV sector will not function without collaborative networks. Drawing on Shankar's specific examples of collaborative partnerships and Engelen's more general analysis of network formation problems, the combined approach can build solid links between stakeholders in India's photovoltaic sector, including manufacturing entities, suppliers, government entities, and research institutions. This would enhance knowledge transfer, resource pooling, and synchronized efforts toward driving circular innovation (Shanker, 2023, Engelen, 2023).

The infrastructure is the second critical element. Engelen's reverse logistics and data infrastructures are particularly relevant in circular management. Shankar's case studies demonstrate the development and optimization of these infrastructures in practical scenarios. Together, they provide a more complete picture of the infrastructural requirements for circular innovation, ensuring effective collection, recycling, and re-use of end-of-life components. Consumer activation and market creation are also important. Shankar stresses customer engagement as a prominent barrier, while Engelen points out the more general problem of consumer awareness and interest. Merging their insights may lead to strategies. Educate and Engage: Considerable consumer education and market-making efforts will help create an enabling environment for circular innovation. Awareness programs about circular products, incentives, and demonstration projects that provide proof of the business case in terms of economic and environmental results make for a receptive market (Shanker, 2023, Engelen, 2023).

The combination of frameworks is flexible enough to adapt nuanced niche strategies to particular issues. Matters relevant to the region would receive local attention. Niche strategies can enable resource sharing and collaboration. Probably, the product-as-a-service model will also disseminate by enhancing the product's accessibility and sustainability, while business models that offer this type of product as a service are likely to become common, thereby ensuring access and sustainability. In summary, a combination of Shankar and Engelen's TIS frameworks will help provide a complete, nuanced approach to understanding the best introduction strategies for India's circular innovation of PV panels. This will guarantee coverage of all the systemic factors that allow the formulation of effective strategies that can pave the way through barriers and drive large-scale adoption of sustainable PV technologies. We can say that an integrated approach would significantly advance circular innovation in photovoltaic panel integration within the Indian context, going a long way toward a more sustainable future by addressing challenges related to regulatory, collaborative, infrastructural, and consumer engagement issues (Shanker, 2023, Engelen, 2023).

Below, you can see the combined indicators per building block in Figure 2.7 and per influencing conditions in Figure 2.8 that were used to adapt the TIS framework for circular innovation by Raghav Shankar Jules Engelen.

Building Blocks	Combined Indicators (Raghav's and Jules')	
Product Performance and Quality	- Design for circularity - Resource optimization	- Integrated PSS - Recycled quality
Product Price	- Long term feasibility - Total cost of ownership - Price disparity	- Circular vs linear price - Extended ROI - Business case challenge
Production System	- 9 R(s) capability - Strong reverse logistics	- Flexibility & Adaptability - Economies of scale
Complementary Products and Services	- Collaboration - Industry specific infrastructure	- Ecosystem of products/services
Network Formation and Coordination	- Strong network - Division of responsibility - Shared goals - Collaboration reluctance - Stakeholder resistance	- Network formation - Convincing partners - Standards absent - Third-party absence
Customers	- Awareness & knowledge - Ownership preferences - Resistance to change	- Customer acceptance - Reaching customers
Innovation-Specific Institutions	- General Consensus - Standardisation - Emerging robust policies - Legislation inconsistency	- Material classification - Regulation clarity - Health & safety
Reverse Logistics	- Recycling infrastructure - Reverse logistics	- Recycling systems - Circular infrastructure

Figure 2.7: Combined Indicators for Building Blocks

Influencing Conditions	Combined Indicators (Raghav's and Jules')	
Knowledge and Awareness of Technology	- Limited scope of circular products - Large scale demonstration	- Design limitations - Concept validation
Knowledge and Awareness of Application and Market	- Uncertain returns - Linear lock-ins - Asymmetric information	- Knowledge gap - Sector knowledge - Impact data
Natural, Human and Financial Resources	- Resource flow optimisation - Leadership & team skills - Availability of finances	- Supply limitations - Capital access - Flow inconsistency
Competition	- Market positioning - Conventional competition - Value proposition	- Material competition - Technology variety - Regulatory strain
Macro-Economic and Strategic Aspects	- Systemic perspective - Economic conditions - Conductive regulations - Policy support	- Tax bias - Raw material bias - CE criteria absence
Socio-Cultural Aspects	- Literacy & motivation - Informed preferences - Limited information & knowledge - Value chain inequality - Counterproductive behavior	- Sustainable disinterest - Business inertia - Process confusion - Reputation risk - Repair limitations
Accidents and Events	- Internal disruption - Cascading effects	- Resilience
Data Infrastructure	- Tracking difficulties	

Figure 2.8: Combined Indicators for Influencing Conditions

2.3. Present Scenario of Solar Waste in India

The management of end-of-life photovoltaic panels will only grow more urgent with time as India presses forward its ambitions to increase installed solar capacity. In this regard, circular innovation is very important for the future because it is one of the key steps forward in the solar sector's struggle to achieve sustainable development. Solar industry can successfully reduce waste generation and resource consumption by adopting business models in the circular economy that prioritize design for re-use, repair, remanufacture, and recycling (Franco and Groesser, 2021).

Against the backdrop of the current state of solar waste management in India, the rapidly growing trend of solar installations in both residential and commercial sectors is a mark of the times. The recycling rate of solar modules itself has remained astonishingly low. Studies have shown that, in 2030, the amount will be 200,000 metric tonnes, while by 2050 it shall be around 1.8 million metric tonnes of PV module waste only from India (Rathore and Panwar, 2022, Waste, 2018). The potentially hazardous materials used in their manufacturing, together with the rapid growth of this waste stream and a lack of proper infrastructure for recycling, mean that the problems present huge challenges. This, therefore, presents a step that tackles the above-mentioned challenges to ensure the validity of the argument in the case for green and sustainable energy from solar energy (Arora et al., 2018, Gautam, Shankar, and Vrat, 2021).

The increasing demand for many of the raw materials used in PV panel technology surpasses the supply in the coming years, making resource efficiency and recycling even more crucial. Only the European Union has passed specific legislation for photovoltaics, despite countries such as the US and Japan having defined methods for recycling and disposing of photovoltaic waste. While there is a great, appalling silence in India about the challenges it faces in managing solar waste, given the lack of regulations or infrastructure for the handling of End-of-Life (EoL) PV panels in the country, some encouraging steps and discourse have recently begun (Jain, Sharma, and Gupta, 2022, Gautam, Shankar, and Vrat, 2021).

2.3.1. The Growing Challenge of Solar Waste

A sign of the consequent time discrepancy, the Indian solar industry has now grown infinitely to more than 67 GW of installed capacity. This growth, while very important to the attainment of the nation's set goals of renewable energy, presents the inevitable accumulation of PV waste as the panels come to the end of their operable life, ranging from 25 to 30 years. This is a huge amount of waste, considering that by the year 2030, the world is expected to have about 200,000 metric tonnes of PV waste and around 1.8 million metric tonnes by the year 2050. In India, however, the infrastructure for solar waste management is still at an absolute fledgling stage. Concerns about the inadequate number of recycling plants and the lack of proper regulatory guidance for managing end-of-life PV panels are growing, raising concerns about the potential environmental and health impacts of improper disposal. Concerns about the leaching of lead and cadmium, the loss of metals, and the depletion of virgin resources due to inappropriate disposal practices are rapidly growing (Jain, Sharma, and Gupta, 2022, Gautam, Shankar, and Vrat, 2021, Rathore and Panwar, 2022, Waste, 2018).

2.3.2. Current Practices in Solar Waste Management

Solar waste management is still in its infancy in India. In contrast, countries in the European Union have established specific legislation regarding the recycling of photovoltaic panels, whereas under Indian rules, PV waste was still classified as general or industrial waste till last year. Consequently, the lack of legislation specifically addressing PV waste management has resulted in sporadic actions, with only a limited number concentrating on recycling and reuse (Gautam, Shankar, and Vrat, 2021).

Only a few, such as Poseidon Solar Services in Tamil Nadu, have taken concrete measures to construct infrastructure for the recycling of solar PV systems. Otherwise, these efforts have been isolated, sparse, and completely inadequate to handle the mass of waste that is likely to come in the future. This kind of noncoordinated development gives way to the risks of environmental contamination and resource depletion. In addition, recycling processes that exist nowadays are mostly primitive and contain only manual extraction of aluminium and copper, with no recovery of value-added products like silicon and metals (Jain, Sharma, and Gupta, 2022).

2.3.3. Environmental and Health Implications

The improper disposal of PV panels poses acute environmental and health risks. PV panels contain hazardous materials such as lead, cadmium, and other heavy metals that can contaminate the soil and water if not managed properly. This exposes the environment and human life to considerable risks, particularly in countries whose practices on waste management are lax. Moreover, the cracking of polymers and other materials from PV panels, caused by their incineration in regular incinerators, can produce harmful gases that accelerate air pollution and underwater acidification, thereby hastening climate change. These environmental and health risks will only rise more marked as the volume of solar waste increases, hence the crying need to come up with proper waste management measures (Gautam, Shankar, and Vrat, 2021). Below, you can see the list of toxic materials used in solar panels in Figure 2.10 and list of health risks associated with the pv panels in Figure 2.9.

Solar Cell Type	**Manufacturing Materials**	**Health Risks**
Crystalline Silicon (c-Si)	HNO3 HF NaOH for cleaning B2H3 POCl3 for doping	Chemical burns Respiratory irritation from fumes POCl3 can produce harmful gases
Amorphous Silicon (a-Si)	Silane gas (flammable) Dopant gases (AsH3, GeH4, PH3)	Flammability and explosion risk from Silane Toxic effects of dopant gases
Cadmium Telluride (CdTe)	CdS CdCl2 CdTe cadmium vapors	Risks from inhaling cadmium vapors Leading to severe respiratory issues
Copper Indium Selenide (CIS)	Copper Indium Selenium in vapor state Selenium hydroxide	Toxicity towards animals Affects mucous membrane Environmental hazards

Figure 2.9: Solar cells associated health risks

Chemical	**Utilisation**	**Asphyxiant**	**Corrosive**	**Irritating**	**Flammable**	**Explosive**
Argon gas	Thin film deposition	✓				
Ammonia	Antireflective coating		✓	✓	✓	
Diborane	a-Silicon dopant	✓			✓	
Helium gas	Thin film deposition	✓				
Boron trifluoride	Dopant				✓	
Hydrochloric acid	x-raw material etching and cleaning		✓	✓		
Hydrofluoric acid	x-cleaning and etching		✓	✓		
Hydrogen Selenide	CIS sputtering	✓			✓	✓
Hydrogen gas	a-deposition	✓			✓	
Hydrogen Sulphide	CIS sputtering	✓			✓	
Nitrogen trifluoride	Si wafer plasma etching	✓				
Methane gas	a-Si & GaAs manufacturing	✓			✓	
Phosphine gas	Thin film dopant	✓			✓	
Phosphorous oxychloride	x-Si dopant	✓			✓	✓
Selenium	CIS & CIGS raw material	✓				
Silane gas	Intermediate product in x-Si production				✓	✓
Silicon tetrachloride	x-Si & a-Si deposition		✓	✓		
Tellurium	CdTe & CIS raw material					
Trichlorosilane	x-Si & a-Si deposition		✓	✓		
Alkali	Cleaning		✓	✓		

Figure 2.10: Potential toxicity of materials used in solar PV panels

2.3.4. Opportunities for Circular Innovation

While the problems associated with solar waste in India are huge, they also point to opportunities for circular innovation. Circular economy practices enable India to alter its approach to managing solar waste, transforming potential environmental disasters into a sustainable industry. The adoption of circular economy business models for solar businesses—in terms of design for re-use, repair, remanufacturing, and recycling is of very great necessity if their models are to reduce waste and resource use (Franco and Groesser, 2021).

Recycling technologies that can efficiently recover the key resources from EoL PV panels offer important opportunities to make investments in recycling infrastructure and research, which may not only minimise the environmental cost of solar waste but also, at the same time, create new economic opportunities in the recycling sector (Gupta, Yadav, and Kumar, 2015). Another critical zone would be the full activation of regulations and policies, providing impetus and opening avenues for circular innovation in the solar sector. This framework must, of course, include guidelines on the recycling and sustainable waste disposal of photovoltaic panels, as well as incentives for companies to engage in circular practices (Gautam, Shankar, and Vrat, 2021).

In this regard, this would require the cooperation of industry stakeholders, manufacturers, recyclers, and policymakers in helping to realize a sustainable solar waste management system. This approach would standardize the process and facilitate the sharing of best practices, thereby integrating circular innovation into the Indian solar industry. More than anything, it is proper education on the disposal and recycling of solar panels that holds the key to successful circular innovation. Interest in circular products and services could increase awareness through campaigns, stimulating demand and pushing consumer and business behaviour towards greener action.

These leveraged opportunities have the potential to make India a leader in creating a sustainable solar industry that will meet the country's energy needs while protecting the environment and public health. All stakeholders must coordinate their efforts to transition to a circular economy in the solar sector, which could yield significant economic and environmental benefits.

2.4. Worldwide PV Waste Trends

As solar energy increasingly dominates the global renewable power landscape, the management of photovoltaic (PV) waste is becoming a critical issue. The growing deployment of solar photovoltaic systems around the world highlights the need for effective end-of-life (EoL) management strategies. Different countries have developed various approaches to classify and treat PV waste, each shaped by unique regulatory, environmental, and economic contexts. This section explores the global trends in PV waste management, focusing on the practices of specific countries, the risks associated with materials used in PV panels, and the latest advancements in recycling technologies.

2.4.1. Global Approaches to PV Waste Management

PV waste management practices vary significantly across countries, driven by distinct regulatory frameworks and the maturity of their recycling industries.

European Union:

With the WEEE Directive in place, the European Union has been at the forefront of photovoltaic waste management. The WEEE Directive is a complex regulation that imposes strict liability on the manufacturers and suppliers of photovoltaic products. Manufacturers must collect, treat, and recycle end-of-life photovoltaic panels under this scheme to ensure their disposal in an environmentally friendly manner. This system requires manufacturers to register their products and update information on materials that meet specific recycling targets. The EU's circular economy is evident in its alignment with environmental concerns at all stages of design and production. Thirdly, these schemes feature a high degree of recycling and recovery. R&I initiatives stimulate the development of new recycling technologies in a variety of ways. The compliance schemes in each member country promote and complement the regulatory framework. These ambitious goals correspond to the broad EU ambitions for environmental sustainability and resource efficiency (Arora et al., 2018).

United States:

On the other hand, in the United States, there is no such consolidated and comprehensive centralized regulatory framework for the management of PV waste materials. Management of PV waste is currently included in the core of the 1976 Resource Conservation and Recovery Act, RCRA, along with general disposal of solid and hazardous wastes. However, because there is no independently designed federal regulation for PV waste, practices vary and are grossly deficient from state to state. California lawmakers, for example, passed legislation that classified EoL photovoltaic modules as universal waste. Otto argues that this classification made it easier for firms to collect and recycle the material, as lower regulatory compliance also promotes more environmentally friendly disposal methods. The private sector in the US continues to be instrumental in driving the circular business practice agenda. For example, one of the largest manufacturers in the US, First Solar, has established a proactive, voluntary take-back and recycling program for its solar panels. This underpins responsible EoL management and, to an additional extent, recovery of strategic materials back into new products. This is by both the government and industry of Japan in managing PV waste (Arora et al., 2018).

Japan:

Japan's approach to managing PV waste is characterized by cooperative governance between the government and industry, supported by national policies that emphasize reuse and recycling. The Waste Management and Public Cleansing Act, along with the Construction Waste Recycling Law, provide the legislative backbone for PV waste management in Japan. We are revising the laws to create a favorable regulatory environment for the disposal and recycling of solar panels. Since 2015, METI and MOE have been collaborating with the Japanese government to develop a road map for the effective disposal management of solar PV EoL waste through recycling. The series of guidelines for effective recycling in the road map encourages the industry to adapt to that across-the-board common practice. Japan's policy framework has advanced the current industrial status by directly incorporating life cycle assessment into the development and manufacturing processes of PV modules, innovating recycling technologies, and maintaining a closed-loop policy in the solar energy sector (Arora et al., 2018).

China:

In contrast, while China has built and installed more PV than any other country in the world, it does not yet have a strategy for EoL PV waste. China's strategy for EoL PV waste is undoubtedly less defined than that of the EU or Japan. Although China has a general, but not fully developed, system for managing electronic waste, its regulations for the specific PV waste stream are still in their infancy (Arora et al., 2018). Nevertheless, we are realizing that the emerging challenge is being addressed at a nascent stage through the formulation of well-rooted policies based on comprehensive environmental initiatives, but without specific legislation for EOL PV solar waste. Already built up, there is funding from the Ministry of Industry and Information Technology to conduct R&D work targeting an improvement in recycling efficiency for crystalline silicon PV module scraps, representing the largest share in the market. The authors, on the other hand, lead several pilot projects implemented by academic institutions and commercial companies to test new recycling technologies and economic models in large-scale PV module recycling (Arora et al., 2018).

South Korea:

South Korea is currently in the initial stages of developing a governance framework for sustainable management of PV waste. Unlike the old EU and Japan, which had more integral media policy responses in the past, South Korea has not yet issued a national policy regarding solar PV waste recycling and disposal, but has strived in its old ways to come up with several R&D projects—though only programs for that matter—

that would establish an efficient process of recycling solar panels. The innovation and technological development approach of South Korea emphasizes development enhancement of resource recovery and recycling means for waste from the PVs. Additionally, during the period, the country engaged in massive international cooperation and knowledge sharing in an attempt to learn from best practices at the global level and embed the insights into the developing framework (Arora et al., 2018).

2.4.2. Risks Associated with Materials Used in PV Panels

Materials that pose a high environmental and health risk in PV include silica, cadmium, lead, and other heavy metals, which could find their way into the environment through improper disposal methods such as landfilling or incineration. It is critical to develop and implement efficient recycling processes for the recovery and reutilization of such materials with the least environmental impact.

Crystalline Silicon Panels (c-Si):
The solar industry widely uses these types of panels, primarily made from materials like silicon, aluminium, and glass. Although silicon is generally considered harmless, its processing is associated with some dangerous chemicals, like hydrofluoric acid, for instance, which have harmful effects if not properly handled. Additionally, the frames used on most c-Si panels are usually aluminium, and solders contain lead. When handled improperly, exposure to these harmful metals can contaminate land and water (Sheoran et al., 2021).

Thin-Film Panels:
Thin-film PV panels using cadmium telluride and copper indium gallium selenide technologies pose greater risks due to their composition with cadmium, a known poison and carcinogen for humans and wildlife. If not recycled, cadmium exposure poses a serious health risk to humans and the environment, as it can leach into the ground through landfills. He pointed out that if eventually released into the environment, cadmium in CdTe and CIGS thin-film solar panels and selenide in CIS panels did have great concerns about environmental implications since it is a highly toxic element (Sheoran et al., 2021).

2.4.3. Advances in PV Recycling Technologies

Growing volumes of EoL PV panels worldwide drive innovation in recycling technologies aimed at enhancing material recovery efficiency and effectiveness. In essence, the challenge for PV recycling is how to separate and purify the materials found in these panels. This necessitates advanced processes that provide absolutely no loss or contamination of high-value materials. As these technologies continue to develop, they will play a critical role in the global effort to manage PV waste sustainably. By investing in these innovations, countries can mitigate the environmental impact of solar waste while creating new economic opportunities in the recycling sector.

Mechanical Recycling:
PV panel recycling processes typically involve mechanical methods for crushing and grinding, followed by practical separation techniques such as sieving, magnetic separation, and eddy current separation. They represent a relatively simple process for recovering materials such as glass, aluminum, and copper, but they are less effective at recovering high-purity silicon or rare metals like silver and indium (Jain, Sharma, and Gupta, 2022).

Thermal and Chemical Recycling:
Since mechanical recycling has its limits, thermal and chemical processes are under development to ensure better separation and purification of materials present in PV panels. Thermal treatment processes involve heating up the panels and breaking down the polymer encapsulants to eventually separate the glass and metals; the other is the chemical process using solvents or acids to dissolve specific components for recovery. Although such processes ensure a highly valuable recovery, most of them are associated with a higher level of complexity and cost (Sheoran et al., 2021).

Emerging Technologies:
New technologies, above all the laser-assisted delamination, open very promising prospects for PV recycling. Those techniques are linked to the use of lasers or other non-thermal methods for separating PV panel layers. For this reason, they minimize contamination, thereby reducing it and significantly increasing the material recovery rate. Other than that, automated disassembly and robotic sorting provide a completely new and more efficient input to the recycling process (Sharma and Pandey, 2020).

2.5. Recycling Process: Crystalline Silicon (c-Si)

Recycling photovoltaic (PV) panels, particularly crystalline silicon (c-Si) panels, is a critical component in the sustainable management of solar energy systems. With c-Si technology dominating the global market—accounting for over 90% of installed PV systems—developing effective recycling processes is essential to minimize environmental impact and recover valuable materials. This section explores the various recycling processes for c-Si PV panels, including module deconstruction, silicon wafer recovery, and the treatment of other key components such as backsheet polymers and encapsulants (Isherwood, 2022).

2.5.1. Module Deconstruction

The recycling process for c-Si PV panels begins with the deconstruction of the modules, a crucial step that involves disassembling the panels into their constituent parts. This separation is essential for recovering materials like glass, aluminum frames, junction boxes, and cables, and it paves the way for more intricate processes aimed at reclaiming the silicon cells and encapsulants (Isherwood, 2022).

Key Steps in Module Deconstruction:

1. **Frame Removal:** The aluminum frame encasing the panel is typically removed first. Aluminum is highly recyclable and can be easily reprocessed.
2. **Glass Separation:** The glass layer, protecting the silicon cells, is separated next. This high-quality glass can be recycled for new products or used in other applications like asphalt production.
3. **Junction Box and Cable Removal:** Junction boxes and cables, often containing copper, are removed and sorted for recycling. Copper is a valuable material that can be efficiently recovered.

2.5.2. Recovery of Silicon Wafers

After the initial deconstruction, focus shifts to the recovery of silicon wafers, the core component of c-Si PV panels. Silicon is a valuable material, and its recovery is crucial for reducing the environmental impact of PV panel disposal. The recovered silicon can then be purified and reprocessed into new wafers, significantly reducing the need for raw silicon and lowering the environmental footprint of PV manufacturing (Isherwood, 2022).

Recovery Techniques:

- **Thermal Treatment:** This method involves heating the panels to break down the encapsulant—usually ethylene-vinyl acetate (EVA)—that binds the silicon wafers to the glass. This process facilitates the separation of silicon wafers from the other materials.
- **Chemical Treatment:** Chemical methods using solvents can dissolve the encapsulant, enabling the silicon wafers to be detached without high temperatures. This approach can result in a higher purity of recovered silicon wafers.
- **Mechanical Separation:** Mechanical processes such as grinding and milling can also recover silicon from PV panels. However, this method often results in the fragmentation of silicon wafers, making them less suitable for reuse in new

PV panels but still valuable for other applications.

2.5.3. Recycling of Crystalline Silicon Cells

Recycling crystalline silicon cells presents unique challenges due to the intricate nature of the materials and the processes involved in their manufacture. These cells consist of multiple layers, including anti-reflective coatings, metal contacts, and the silicon substrate itself (Isherwood, 2022).

Challenges:

- **Material Contamination:** During recycling, silicon wafers can become contaminated with metals from contacts or residues from the encapsulant, affecting the quality of the recycled silicon.
- **Efficient Separation:** Separating different materials in a silicon cell without damaging the silicon substrate is challenging. Aggressive techniques can reduce the purity and quality of the recovered silicon.

Opportunities:

- **Advanced Purification Technologies:** Developing advanced purification processes can improve the quality of recycled silicon, making it suitable for new PV cells. Techniques such as float-zone purification or chemical vapor deposition (CVD) can achieve the high purity required for solar-grade silicon.
- **Material Reuse:** Even if the silicon cannot be reused for new PV cells, it remains valuable for other industries, such as electronics or as raw material for producing solar-grade silicon through further processing.

2.5.4. Backsheet Polymers

The backsheet of a PV panel is typically made from durable polymers designed to protect the silicon cells from environmental damage. However, these polymers pose recycling challenges due to their complex chemical compositions and the difficulty of separating them from other panel components. Given the challenges associated with backsheet recycling, ongoing research is focused on developing more efficient and environmentally friendly methods for processing these materials (Isherwood, 2022).

Recycling Processes:

- **Mechanical Recycling:** This process involves shredding the polymers into smaller pieces, which can then be reprocessed into new products. However, this often degrades the polymer quality, limiting its reuse.

- **Thermal Recycling:** Thermal recycling, or pyrolysis, breaks down polymers into simpler chemical compounds that can be reused in producing new plastics. This process can recover valuable materials but requires careful control to avoid releasing toxic emissions.

2.5.5. Encapsulants

Encapsulants, typically made from EVA, protect silicon cells from moisture and mechanical damage. However, they also present one of the biggest challenges in PV panel recycling due to their adhesive properties, making it difficult to separate them from the silicon wafers. As encapsulant recycling technology evolves, it will play a critical role in enhancing the overall sustainability of PV panel recycling (Isherwood, 2022).

Current Methods:

- **Thermal Decomposition:** This common method involves burning off the EVA in a controlled environment, allowing the silicon wafers and glass to be separated. However, this process can release harmful emissions if not properly managed.
- **Chemical Solvents:** Newer approaches use chemical solvents to dissolve the EVA, enabling the recovery of silicon wafers without the need for high temperatures. This method can be more environmentally friendly and lead to higher material recovery rates.

Innovations:

- **Laser-Assisted Delamination:** A promising innovation is the use of laser technology to precisely cut through the encapsulant without damaging the underlying silicon wafers. This method reduces contamination risk and improves recycling efficiency.

This figure 2.11 shows different commercial recycling process available worldwide for crystalline silicon solar panels (Radziemska, Ostrowski, and Seramak, 2009, Doni and Dughiero, 2012, Isherwood, 2022, Wang et al., 2019, Niekurzak et al., 2023, Kokul and Bhowmik, 2021, Chen et al., 2021, Prado, Tenório, and Espinosa, 2017).

Name	Stage of Process	Method Used	Materials Recovered
Chemical Treatment	Chemical Processing	Etching of electric connectors, ARC, and n-p junction layer	Pure Silicon
Electrothermal Heating Process	Separation	Electrothermal heating for delamination	Glass and Silicon
Mechanical Crushing and Delamination	Initial Deconstruction	Mechanical crushing and shredding	Aluminium, Copper, Glass (contaminated cullet)
Pyrolysis-Based Separation	Delamination and Recovery	Two-stage heating treatment	TPT backing materials, Glass, Silicon Wafers
Semi-Automatic Recycling Line	Delamination	Thermal delamination method	Materials for laboratory-scale recycling
Recycling to Modified Composite Products	Material Repurposing	Powdering and blending with recycled polymers	Composite Tiles for Furniture
Recovery of Valuable Materials	Material Recovery	Leaching and dissolving impurities	Silicon (Si), Silver (Ag), Copper (Cu), Tin (Sn), Lead (Pb)
Isopropanol-Based Separation	Encapsulant Removal	Using isopropanol as solvent	Semiconductor Wafer, Glass, Ribbon, Backsheet

Figure 2.11: Summary of Recovery Processes and Materials

2.6. Drivers to PV Recycling in India

The growing size of India's solar energy industry necessitates an equally effective recycling of photovoltaic panels. However, the implementation of circular economy principles in the PV industry hinges on comprehending the primary factors that could propel the development and implementation of recycling procedures. Beyond just the energy and environment-related impacts due to PV waste, these drivers will be critical in taking care of the country's needs and building an overall sustainable solar industry. This section not only outlines the primary drivers that would push India towards a strong and efficient PV—a recycling ecosystem—but also discusses opportunities laying ahead for the stakeholders, policymakers, and civil society at large. This emphasizes the need to study and implement PV panel recycling in India, and gives rise drivers for PV recycling as listed in figure 2.13 (Jain, Sharma, and Gupta, 2022, Gautam, Shankar, and Vrat, 2021, Goyal, Esposito, and Kapoor, 2018).

Drivers	Description
Increasing Energy Demands	India's population growth, urbanisation, and modernisation are significantly increasing the demand for energy. This surge necessitates the adoption of sustainable energy solutions, positioning PV systems as a reliable and environmentally friendly energy source.
Augmentation of Solar Capacity	India's ambitious target to achieve 100 GW of solar capacity by 2022 underscores the dramatic augmentation of solar power installations. Solar energy is seen as a reliable and efficient source, contributing to the country's sustainable energy goals.
Premature PV Waste Generation	Premature generation of PV waste due to damage during transportation, installation, operation, or natural calamities like floods and earthquakes presents a challenge. This emphasizes the need for robust systems to manage and mitigate such waste effectively.
High Dependence on Imports	India's high dependence on imports for the production and installation of solar PVs creates a strategic vulnerability. Developing a circular economy can reduce reliance on imported materials by enhancing recycling and reuse practices.
Availability and Affordability of Materials	The dedicated availability and affordability of constituent materials required for the manufacture of solar PV systems support the feasibility of circular practices. Efficient recycling can ensure a steady supply of these materials, reducing the need for virgin resources.
Projected EOL PV Waste	India is expected to produce 2.95 billion tonnes of end-of-life (EOL) solar PV waste, including PVs and balance of system (BOS) components, between 2020 and 2047. This projection highlights the urgent need for sustainable waste management strategies.
Hazardous Materials in PV Waste	The presence of hazardous materials like lead, lithium, tin, and cadmium in PV waste poses significant environmental risks. Unscientific disposal can lead to soil and water pollution, necessitating effective recycling and disposal methods.
Critical Metals Supply Crunch	The competitive consumption and supply crunch of critical metals such as silicon, germanium, and lithium used in manufacturing solar panels underline the importance of recycling. Ensuring the recovery and reuse of these metals can mitigate supply chain risks.
Regulatory Gaps	Currently, there is no specific definition of solar PV waste in India's waste management guidelines, and it is treated as general e-waste under the Ministry of Environment, Forest and Climate Change (MoEF&CC). Clear regulations tailored to PV waste are essential for effective management.
Need for Regulations and Incentives	Appropriate regulations and incentives are required to transition solar PV management from a linear to a circular economy. These measures can promote sustainable practices and support the development of a robust recycling infrastructure.

Figure 2.12: PV Panel Recycling Drivers

2.7. Barriers to PV Recycling in India

Despite the strong drivers of PV recycling in India, the solar industry must overcome significant barriers to fully realize the potential of a circular economy. This implies that there are economic, technical, regulatory, and infrastructural barriers that stand in the way of progress for the recycling initiatives and the diffusion of more sustainable practices. We need to comprehend these obstacles to develop targeted strategies that can overcome them, making PV panel recycling in the nation a reality. This therefore concludes this section of the literature review, but it lays the groundwork for further discussion on how these excesses could be handled better for a more sustainable future for India's solar energy sector. The key barriers to PV recycling in India are identified, studied and reviewed by Jain, Sharma, and Gupta, 2022, Gautam, Shankar, and Vrat, 2021, Goyal, Esposito, and Kapoor, 2018 and a summary of it is provided in the figure 2.13

Barrier	Description
Absence of Definition	Absence of even a definition of solar PV waste in India's waste management guidelines and its being treated as general e-waste managed under the Ministry of Environment, Forest and Climate Change (MoEF&CC)
No Specific Regulations	India has no specific regulations for solar module waste disposal, and the waste is dumped in an unscientific manner into landfills
Lack of Policy Regulations	Lack of policy regulations to streamline the collection, recovery, and recycling of solar PV waste
Lack of Formal Recycling Facilities	Lack of formal recycling facilities to detach the glass and aluminium used in solar PV modules
Non-inclusion of BOS	Non-inclusion of BOS (inverters, batteries, etc.) under the E-waste management rules, 2016
Lack of Accountability	Lack of accountability within the industry for managing solar PV waste at the EOL stage
Lack of Coordination	Lack of coordination among various stakeholders of the solar industry like relevant ministries, authorities that issue tenders, manufacturers, and industry stakeholders
Lack of Economic Incentives	Lack of economic incentives for recyclers and manufacturers to enter the business of EOL management of solar PV waste
Lack of Consumer Awareness	Lack of consumer awareness and participation in EOL solar PV waste recycling
Appropriate Regulations and Incentives	Appropriate regulations and incentives are required for the transition of solar PV management from a linear to a circular economy
Product Stewardship Approaches	Product stewardship approaches like Extended Producer Responsibility (EPR), mandatory joint collection and recycling schemes, and shared responsibility among stakeholders are possible strategies
Innovative PV Waste Management Systems	Design and implementation of innovative PV waste management systems are necessary: e.g., circular business models like buy-back, deposit-refund systems, and product-servicing to promote industry development and transition towards a circular economy
Promotion of R&D Initiatives	Promotion of R&D initiatives in relation to EOL management of solar PV waste for evaluating new and effective technologies and designs of solar PVs
MNRE Blueprint	In April 2019, the MNRE issued a blueprint for the disposal, utilisation, manufacturing, and import of solar PV equipment, but no on-ground implementation has occurred

Figure 2.13: PV Panel Recycling Barriers

3 Research Methodology

The design of the study for this research combines a mixed-method approach where niche strategies for circular innovation of EoL PV panel in India will be identified by applying qualitative method. This approach is chosen to provide an overview of drivers, barriers, and strategies associated with circular innovation with particular focus on recycling. It applies the TIS framework, adapted and combined from Raghav Shankar, Jules Engelen, Dr. Ortt, and Dr. Kamp. The research design will then be structured in three phases:

3.1. Phase 1: Literature Review

In the first phase, the design of the research proposes to undertake extensive literature surveying for building up a rudimentary background understanding of TIS as a framework, its relevance with circular innovation, and the current status of photovoltaic recycling in India. This would be a very critical phase in setting the context and theoretically underpinning latter phases of the research.

3.1.1. TIS Framework

Development of the TIS Framework

Dr. Ortt and Dr. Kamp combined insights from socio-technical systems literature and the innovation and strategic management literature in the TIS framework and brought seven building blocks and seven influencing conditions that can influence the building blocks. The Technological Innovation System building blocks in the framework are product performance and quality; product price; production system; complementary products and services; network formation and coordination; customers; and innovation-specific institutions. The influencing conditions in the framework are: knowledge and awareness of technology; knowledge and awareness of application and market; natural, human and financial resources; competition; macro-economic and strategic aspects; socio-cultural aspects; and accidents and events. All these elements put together make it possible to understand. This shapes the dynamics of the innovation system and interactions between the many actors, institutions, and technologies involved. It is used to analyze context conditions within which an innovation finds itself in its early development phases and for formulation of niche introduction strategies (Ortt and Kamp, 2022).

Adaptations for Circular Innovation

The original TIS framework has been adapted for circular innovation by previous TU Delft students Raghav Shankar and Jules Engelen. Their adaptations focus on the specific challenges and opportunities presented by circular innovation.

Raghav Shankar's Adaptation Shankar directs his research toward Dutch high-tech companies and adjusts the framework of TIS for circular innovation in this context. He points to some key drivers among emerging regulations, collaborative partnerships, strategic product design, and intrinsic motivation. Shankar also provides barriers like complex production systems, complementary products and services, formation challenges of the network, and problems in customer engagement. Shankar has suggested a number of niche strategies to surmount the identified barriers, such as the Redesign Niche Strategy, Decentralization Niche Strategy, Turnkey Product-Service System Niche Strategy, and Compliance-Driven Stepping-Stone Niche Strategy. He also considers how these strategies play out in practice to overcome barriers and to support circular innovation more generally (Shanker, 2023).

Jules Engelen's Adaptation Engelen goes for a broader approach relying heavily on a systematic literature review. He explores whether, and how, several actors and factors may influence the ways of diffusing circular innovation from a system perspective. These obstacles include consumer knowledge gaps that Engelen has found in the process, problems in the formation of adequate networks, an absence of relevant circular infrastructure, price differences, and policy conditions which are not favorable. He proposes changes in the TIS framework by introducing reverse logistics and data infrastructure as new core factors. Engelen also comes up with niche strategies: the local strategy, the awareness strategy, the design for circular behavior strategy, the product-as-a-service strategy, and the platform strategy (Engelen, 2023).

Combining Existing Frameworks

This study, therefore, integrates elements from the TIS frameworks adapted by Shankar and Engelen, with additional contribution by Dr. Ortt and Dr. Kamp. On one hand, the integration synthesizes the features of the builing blocks and influencing conditions considered within the two adaptations, representing their strong points. It considers drivers, barriers, and conditions extracted in previous phases of this research that influence the innovation system. This combined framework enables understanding the systemic dynamics of circular innovation through complementary insights from Shankar's case studies and Engelen's systematic analysis.

3.1.2. Literature Review Structure

The literature review is structured into several key sections, each addressing different aspects of circular innovation and PV recycling. The structure follows the outline presented in Figures

Circular Economy

This section explores the principles of the circular economy, focusing on the concept of circular innovation. It includes a detailed discussion on how circular innovation can drive sustainable practices in various industries, with an emphasis on PV recycling.

TIS Framework

This part delves into the TIS framework, explaining its core components and their relevance to technological innovation. The adaptations made by Raghav Shankar and Jules Engelen are highlighted, showcasing how the framework can be applied to analyze circular innovation within the PV industry.

Present Scenario of PV Recycling

An in-depth analysis of the current state of PV recycling in India is presented. This includes a review of the existing literature on the recycling processes, challenges, and opportunities specific to the Indian context. The section is further divided into the following subsections:

- **Worldwide PV Waste Management:** An overview of global practices and policies related to PV waste management, providing a comparative perspective.
- **Country-wise Categorization:** A detailed analysis of how different countries approach PV waste management, highlighting best practices and lessons learned.
- **Risks of Materials Used:** Examination of the environmental and health risks associated with the materials used in PV panels, emphasizing the importance of effective recycling processes.

Recycling Processes

This section reviews various PV recycling processes, discussing their effectiveness, technological advancements, and the challenges faced. It is subdivided into the following topics:

- **Module Deconstruction:** Analysis of the methods used to dismantle PV modules.
- **Crystalline Silicon:** Review of the recycling processes for crystalline silicon PV panels.
- **Recycling of Intact Silicon Wafers:** Examination of the techniques for recycling intact silicon wafers.
- **Recycling of Crushed Modules:** Discussion on the methods used for recycling crushed PV modules.
- **Backsheet Polymers:** Analysis of the recycling processes for backsheet polymers used in PV panels.
- **Encapsulant:** Review of the techniques used to recycle encapsulant materials.

Drivers and Barriers to PV Recycling in India

This chapter identifies and analyses the critical drivers and barriers to PV recycling in India operationalized as those which either facilitate or hinder the use of circular practices within the PV sector. This is followed by discussions into the regulatory and strategic responses that could be taken to overcome identified barriers and promote recycling.

3.2. Phase 2: Identifying Barriers, Influencing Conditions, and Introduction Strategies

The second phase of this research had the objective of understanding in detail practical challenges and systemic factors influencing End-of-Life photovoltaic panel recycling in India. This phase aimed at empirical data collection with stakeholders through interviews, identification of the main barriers, understanding the influencing conditions, and proposal of niche strategies within the context of India. In this way, it provided a very solid framework to tackle the complexities of circular innovation within the PV sector.

3.2.1. Systematic Literature Review

A thorough systematic literature review was conducted to gather existing knowledge on circular innovation, particularly concerning PV panel recycling. This review served as a foundation for understanding the current state of knowledge, identifying gaps, and setting the stage for subsequent empirical research. The literature review process included the following steps:

Literature Search and Selection

- Electronic databases such as Google Scholar and Scopus were utilized to search for relevant literature using keywords like ”circular innovation,” ”PV panels,” ”solar,” ”recycling,” ”end-of-life management,” and ”India.”
- Inclusion criteria focused on publications from the last one decade, relevance to the PV sector and circular economy, and emphasis on recycling within circular innovation.

Review and Synthesis

- The literature was reviewed and synthesized to identify key drivers, barriers, and strategies from academic journals, industry reports, and policy documents.
- This synthesis provided a comprehensive understanding of the theoretical and practical aspects of PV recycling and circular innovation.

3.2.2. Stakeholder Interviews

To gain in-depth insights into the practical challenges and opportunities for circular innovation, semi-structured interviews were conducted with key stakeholders in the PV industry, including manufacturers, recyclers, policymakers, and researchers. These interviews were crucial for understanding the ground realities and gathering nuanced perspectives that are not typically captured in literature.

Interview Design and Participants

The interview guide was meticulously developed based on the findings from the literature review, ensuring that all relevant themes and questions were addressed. The guide was structured around the building blocks, barriers, and drivers identified in the literature and aimed to explore:

- Current practices and challenges in managing EoL PV panels.
- Perceptions of barriers to implementing recycling strategies.
- Potential drivers and incentives for adopting circular practices.
- Recommendations for policy and industry actions to promote circularity.

Participants were selected using purposive sampling to ensure a diverse representation of stakeholders in the PV industry. The sample included representatives from PV panel manufacturers, government agencies, and academic institutions. Invitations to participate in the study were sent via email and LinkedIn, and interviews were scheduled based on participants' availability.

INTERVIEWEE	COMPANY TYPE	COMPANY PROFILE
INTERVIEWEE 1	Private Organization – Solar Manufacturing and EPC.	The company is one of India's leading solar power companies. It specializes in the manufacturing of high-efficiency solar photovoltaic (PV) modules, providing EPC (Engineering, Procurement, and Construction) services, project development, rooftop solutions, and solar water pumps.
INTERVIEWEE 2	Researcher	The researcher works in energy and sustainability, focusing on circular economy and waste valorization, making his work highly relevant to PV panel recycling.
INTERVIEWEE 3	Umbrella Organization Policy advocacy	The organization plays a key role in policy advocacy and international cooperation in the solar industry like collaboration with Dutch circular economy focused firms and Indian energy solutions companies, potentially influencing PV panel recycling strategies in India.
INTERVIEWEE 4	Private Organization – Solar Manufacturing and EPC.	The company specializes in innovative solar solutions, making it directly relevant to discussions on PV panel recycling and sustainable practices in the solar sector.
INTERVIEWEE 5	Private Organization – Solar EPC.	The company is involved in solar EPC services with a focus on promoting solar energy and sustainability.
INTERVIEWEE 6	Sustainable Energy Solutions Startup.	The startup is focused on renewable energy technologies, including solar solutions, which could involve innovative approaches to PV panel recycling.

Figure 3.1: Overview of Interviewees

Data Collection and Analysis

Interviews were conducted via the online platform MS Teams. With explicit permission, all interviews were meticulously recorded and transcribed verbatim. The transcriptions underwent a rigorous review process to ensure accuracy and to anonymize any identifying information, thereby safeguarding participant confidentiality.

Manual Analysis of Interview Transcripts In this research, the decision to conduct a manual analysis of interview transcripts, as opposed to using coding software, was guided by several key factors that made manual analysis more suitable for the objectives and context of the study. The nature of the research, the specificities of the data, and the need for a nuanced understanding of the interview content collectively underscored the benefits of a manual approach.

Rationale for Manual Analysis

- **Nuanced Understanding of Contextual Details:** Manual analysis allowed for a more in-depth and contextual understanding of the interview transcripts. Given the complex and multi-faceted nature of PV recycling in India, capturing the subtleties in the responses was crucial. Automated coding software may overlook these finer details, leading to a potential loss of valuable insights.
- **Flexibility in Categorization:** The interviewees, hailing from diverse backgrounds and sectors, often used varied terminologies and economic jargon to describe similar concepts. Manual analysis provided the flexibility to categorize and sub-categorize keywords dynamically, adapting to the diverse linguistic expressions used by the participants. This adaptability is often limited in coding software, which relies on predefined codes and may not efficiently handle the variability in language.
- **Thematic Exploration:** Manual analysis facilitated a thematic exploration of the data, allowing for the identification of overarching themes and patterns across the interviews. By manually sorting and categorizing keywords, it was possible to create a structured framework that captured the essence of the discussions more effectively than a purely code-based approach.
- **Direct Interaction with Data:** Engaging directly with the data through manual analysis ensured a closer connection to the material. This direct interaction helped in maintaining the researcher's familiarity with the data, enabling a more intuitive and informed analysis. The process of reading, annotating, and categorizing the transcripts by hand promoted a deeper immersion in the content.

Methodology of Manual Analysis The manual analysis of the interview transcripts involved a systematic and iterative approach, designed to ensure thoroughness and accuracy in capturing the key insights from the data. The process can be outlined as follows:

1. **Initial Reading and Familiarization:** The first step involved a thorough reading of each interview transcript to gain an overall understanding of the content and context. This initial pass helped in identifying preliminary themes and areas of interest.
2. **Keyword Identification and Categorization:** Keywords and phrases relevant to the research objectives were identified and highlighted. These keywords were then categorized into broad themes based on their context and meaning. For instance, terms

related to technological challenges, economic barriers, policy issues, and socio-cultural factors were grouped under respective categories.

3. **Sub-Categorization of Keywords:** Within each broad category, further sub-categorization was carried out to refine the analysis. This involved breaking down the broad themes into more specific sub-themes. For example, under the category of technological challenges, sub-themes such as ”material degradation,” ”recycling processes,” and ”technological gaps” were identified.
4. **Thematic Mapping:** A thematic map was created to visualize the relationships between different categories and sub-categories. This map helped in identifying connections and overlaps between themes, facilitating a more comprehensive understanding of the data.
5. **Iterative Review and Refinement:** The analysis process was iterative, involving multiple rounds of review and refinement. As new insights emerged, the categories and sub-categories were adjusted to ensure that all relevant aspects were captured accurately. This iterative approach allowed for continuous improvement and refinement of the analysis.

The insights gleaned from the interviews were then utilized to refine the combined TIS framework and to pinpoint relevant niche strategies, ensuring a robust and contextually grounded analysis.

3.2.3. Identifying Barriers and Influencing Conditions

The combined TIS framework was employed to systematically identify key barriers and influencing conditions that affect the development and diffusion of circular innovation in the PV sector. These barriers and conditions were mapped to specific components of the TIS framework, providing a detailed understanding of the systemic challenges involved. This analysis helped to identify critical points of intervention and areas where targeted strategies could be most effective.

3.2.4. Identifying Introduction Strategies

Based on the analysis of barriers and influencing conditions, the study identified niche introduction strategies that could help overcome these challenges.

3.3. Phase 3: Adapting the Framework for Circular Innovation of PV Panels in India

The third phase of this research was dedicated to adapting the Technological Innovation System (TIS) framework to suit the specific context of circular innovation in the photovoltaic (PV) sector in India. This phase was crucial in creating a comprehensive analytical tool that addresses the unique challenges and opportunities associated with PV recycling in India. The adaptation process was thorough, ensuring that the framework would be both robust and relevant.

3.3.1. Identifying Barriers and Drivers through Literature and Interviews

The adaptation began with a comprehensive literature review and semi-structured interviews with key stakeholders, including manufacturers, recyclers, policymakers, and researchers in the PV industry. The literature review provided a theoretical foundation, identifying general barriers and drivers for circular innovation. The interviews offered practical insights into the specific challenges and opportunities within the Indian context.

3.3.2. Adaptation and Integration

Specific indicators for each building block and influencing condition were developed, based on the identified barriers and drivers. These indicators were made very specific and actionable so that their attainment would mean that the respective building block was completed. The formulated indicators were iteratively perfected with insights from the interviews. This iterative process gave a framework that was conceptually sound and practically applicable to the Indian context.

The final adapted TIS framework on circular innovation in the Indian PV sector involved indicators for each building block and influencing condition, tailored to the context of PV recycling in India. This would therefore provide a very sound basis for understanding the systemic dynamics of circular innovation and for formulating effective strategies toward sustainable practices for the PV industry.

The adapted framework has shelved and merged elements from the TIS frameworks of Raghav Shankar and Jules Engelen in order to embed the strengths of those two work pieces into the specific needs existing in the Indian context. Further, this combined approach would ensure comprehensiveness in the framework to handle the divergent challenges associated with circular innovation in the Indian PV sector.

4
Results

Chapter 4 discusses the research findings, including the insights gained from interviews, the analysis of barriers, the creation of niche strategies, and the modification of the TIS framework to suit the Indian context. This chapter aims to provide a comprehensive overview of the key insights gained from the empirical investigation, as well as their implications for the circular innovation of PV panels in India.

The chapter starts with an analysis of the interviews conducted in Section 4.1 with key stakeholders in the PV industry. These interviews provide valuable insights into various aspects of PV panels per building block. We examine the interviews for each building block, noting the identified barriers directly beneath the analysis in subsubsection 4.1.1. We then proceed to discuss the factors that influence these barriers and devise an appropriate niche introduction strategy to surmount them.

Section 4.2 of the chapter adapts the TIS framework for the circular innovation of PV panels in India. To make this change, we need to find the right building blocks, change the conditions that are unique to India's current PV recycling industry, and then combine it with the framework for circular innovation that we talked about in Chapter 2 and Figures 2.8 and 2.7. The section provides a thorough examination of these elements and explores how they can be effectively aligned to foster circular innovation.

4.1. Interview Analysis:

4.1.1. Product Performance and Quality:

In India, the recycling process for solar panels, particularly for the aluminium frames and glass coatings that constitute around 80-85% of the panel's total weight, is being effectively managed. Interviewees (1, 2, 3, 4, 5, 6) consistently reported complete recycling of these components. Nevertheless, the process of recycling silicon, a crucial component in solar panels, poses notable technological obstacles. The integration of silicon with EVA lamination significantly reduces its purity and usability, posing a significant challenge for recycling (Interviewees 1, 2, 3, 4, 5, 6). The economic feasibility of recycling valuable minerals such as silver and copper presents obstacles to the establishment of large-scale recycling facilities (Interviewee 4, 5). In India, the technology for recycling photovoltaic (PV) panels is available. However, implementation and affordability challenges impede the establishment of extensive recycling facilities. Interviewees 2 and 4 mentioned implementation issues, while Interviewees 1, 3, 4, and 6 raised concerns about affordability.

Despite the difficulties, there are growing attempts in the sector to improve recycling procedures. However, Interviewees 1, 2, 3, 4, 5, and 6 report limited implementation of these initiatives. India has not yet established a fully developed sector for recycling solar panels. Nevertheless, there are continuous endeavours to enhance the take-back system, which are essential for improving the efficiency of the recycling process (Interviewees 2, 4, 6). Several prominent Indian solar enterprises are now adopting the principles of the circular economy. The fundamental goal of these principles is to not only improve recycling technologies, but also to decrease material consumption and prolong the lifespan of objects through enhanced design and maintenance (Interviewees 1, 5). In addition, a prominent American company has set up an internal recycling facility near its solar production plants in India, demonstrating a praiseworthy dedication to recycling (Interviewee 3). It is imperative to recognise that the quality of recycled materials can vary depending on the recycler and the specific techniques they employ (Interviewees 1, 2, 5). Furthermore, the recycled materials have a broader scope of possible applications beyond the solar industry (Interviewees 1, 4, 5).

Thus, this block might be considered partially complete since several small-scale recycling efforts are underway, namely for photovoltaic (PV) recycling. While exposure and usage naturally deteriorate silicon quality over time, the degradation resulting from recycling is relatively insignificant. This suggests that current technological capabilities can effectively manage the impact on material quality.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *Recycling may cause degradation of the quality of recovered silicon (Interviewees 1, 2, 3, 4, 5, 6)*

  Influencing conditions for the identified barriers

  - *Knowledge and Awareness of Technology:*

    Ensuring the high quality of silicon is essential for its successful reutilization in the context of solar panel recycling, presenting a significant obstacle (Interviewees 1, 2, 3, 4, 5, 6). A significant concern is that the current recycling systems lack the necessary level of development to efficiently manage the complexities of silicon recovery without causing harm. Silicon, an essential component of solar panels, sometimes becomes contaminated or undergoes a deterioration in its structural integrity during the recycling process. As a result, the final product may be of lower quality and may not meet the strict standards required for high-efficiency solar panels. This diminishes the economic feasibility and appeal of recycling initiatives, as reported by Interviewee 2 and 4.

In addition, the current methods for recycling silicon include subjecting the material to elevated temperatures and chemical treatments, which exacerbate its deterioration. India does not generally use or optimize the available technology to address these issues. Interviewees 3, 4, and 5 attribute a lack of awareness and comprehension to the limited acceptance of advanced recycling technologies and procedures that could effectively maintain silicon quality.

Furthermore, there is a lack of technological expertise at the operational level, resulting in insufficient training for workers and technicians on the most effective methods for handling and processing silicon during recycling. The absence of specialized training and experience worsens the deterioration problem, as mishandling can further undermine the material's quality (Interviewee 6).

Niche Strategies

– *Demo, experiment, and develop niche strategy:*

This strategy entails demonstrating the product in a controlled manner in order to further develop the technology and improve its quality. Experimenting in a research setting can help overcome technological barriers to silicon recycling. The industry can develop better methods to recycle silicon without degrading its quality by focusing on pilot projects and monitored experiments, akin to testing new semiconductor technologies in monitored environments before mass production.

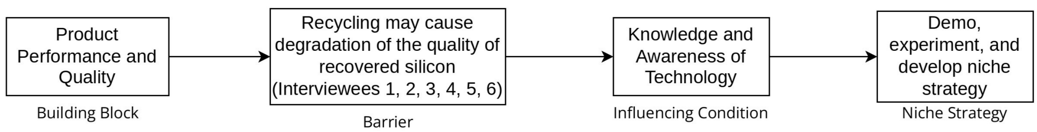

Figure 4.1: Analysis of Product Performance and Quality

4.1.2. Product Price:

The high cost of recycling solar panels hinders the industry's growth. Costs include the initial investment in advanced recycling facilities and transportation of solar panels from installation sites (Interviewees 3, 4, 5, 6). Recycling solar panel materials, including the aluminium frame and glass cover, is economically viable as they retain their excellent quality and may be sold at comparable costs to new materials. Other metals, such as copper and silver, are more problematic to recover and sell. Effective recovery of copper brings in high prices but is uncertain and labor-intensive. Silver, used only in small quantities in photovoltaic cells, can only be recycled profitably in huge amounts (Interviewees 1, 3, 4, 5, 6).

Damage during maintenance, transit, and installation primarily creates solar panel waste, not when the panels reach their end of life. The main obstacle to the collection of these solar panels is the lack of a proper waste collection system. It involves a high cost to build a new solar panel material recycling plant; without government subsidy, it might bring a loss to the enterprise (Interviewees 1, 3, 4, 6). The amount of solar panel trash is expected to increase as more systems approach their end of life. This expansion has the potential to boost recycling profits through economies of scale. Government incentives and subsidies for using recycled components and developing reverse logistics could boost the solar panel recycling industry's economic sustainability (Interviewees 3, 4, 5, 6). Financial support can offset high startup and operational costs, making recycling a more viable choice for firms.

This block can be considered incomplete. The solar panel recycling sector faces financial and logistical problems, but with appropriate government policies and industry advances, it has the potential to become more profitable and sustainable.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *High initial setup and reverse logistics costs (Interviewees 3, 4, 5, 6).*
  Influencing conditions for the identified barriers
  - *Knowledge and Awareness of Technology:*

    The high initial costs are partly due to a lack of widespread knowledge and awareness of the most efficient and advanced recycling technologies available. Advanced technologies that could reduce costs through more efficient processes are not universally known or adopted within the industry. This gap in technological knowledge means that many recycling facilities may not operate at optimal efficiency, leading to higher setup and operational costs (Interviewees 3, 4, 5, 6).
  - *Natural, Human, and Financial Resources:*

    Establishing a new recycling facility specifically for solar panel materials requires a significant financial outlay, not just for the technology, but also for the physical infrastructure and skilled human resources required to operate these facilities. Without substantial financial resources or governmental subsidies to offset these costs, companies face potential financial losses, making it a high-risk investment (Interviewees 3, 4, 6). Additionally, the logistics of collecting and transporting solar panel waste adds to these costs, particularly in the absence of an established system for managing these operations efficiently.

- *Economic viability of recycling certain materials (Interviewees 1, 3, 5, 6).*

  Influencing conditions for the identified barriers

  - *Knowledge and Awareness of Application and Market:*

    Some materials' recyclability is determined by their end-market demand and price fluctuations. The sophisticated and expensive recovery processes involved in recovering these metals make them economically unviable if the volumes recovered are insignificant. The lack of proper market analysis, which aims to understand potential demand for the recycled material (Interviewees 1, 3, 4, 5, 6), further compounds this problem.

  - *Macro-economic and Strategic Aspects:*

    The recycling industry, at a strategic level, requires a stable and predictable market for its products in order to justify investment in technologies and processes for its recyclables. Uncertainty in market prices or demand may deter investment in recycling infrastructure, affecting industry growth and economic viability (Interviewees 1, 3, 4, 6). A well-defined strategic framework will support stable market conditions to make recycling economically attractive.

- *Lack of subsidies and incentives (Interviewees 3, 4, 5, 6).*

  Influencing conditions for the identified barriers

  - *Natural, Human, and Financial Resources:*

    This is crucial because it impacts the accessibility of the financial resources needed to establish and maintain a recycling enterprise. Government subsidies can significantly reduce the financial burden on enterprises, enabling them to invest in recycling technology and infrastructure (Interviewees 3, 4, 5, 6). If not addressed, the substantial upfront and ongoing expenses will continue to hinder the sector's expansion.

  - *Macro-economic and Strategic Aspects:*

    As a result, government strategic initiatives such as subsidies or incentives turn out to be critical drivers of the economic landscape for this industry. Policies that provide financial support and incentives to businesses that use recycled materials increase their economic viability. This is also a means to foster the establishment of reverse logistics systems, which reduces costs further and improves efficiency (interviewees 3, 4, 5, 6).

  Niche Strategies

  - *Top niche strategy:*

    Focusing on high-value market segments where customers are willing to pay a premium can help offset initial costs and improve economic viability. For instance, the recycling of rare materials from PV panels for high-tech applications can lead to higher prices, much like the premium sales of highly purified recycled aluminium.

– *Redesign Niche Strategy:*

  Redesigning the recycling process to be more cost-effective can boost economic viability. This strategy focuses on simplifying the product or process to reduce costs and resources needed. It helps adapt the technology to better meet market demands and improve economic feasibility.

– *Subsidized niche strategy:*

  Providing subsidies can make recycling more economically viable, especially for high-cost initial setups and logistics. This is critical for lowering entry barriers for new recycling facilities, similar to subsidies provided for renewable energy projects.

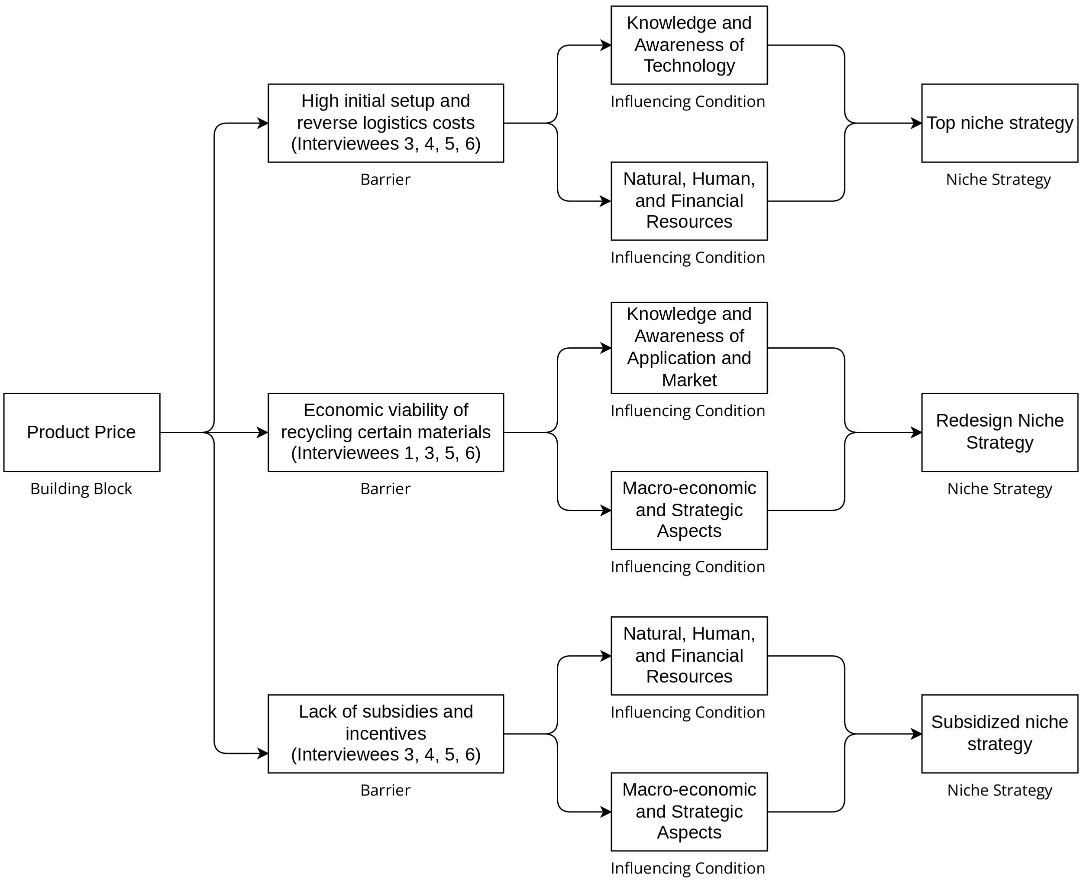

Figure 4.2: Analysis of Product Price

4.1.3. Production System:

Although various e-waste management facilities in India can potentially recycle PV panels, the lack of specific facilities definitely hinders the development of recycling processes for PV panel waste. General e-waste facilities lack the technological expertise to recover certain metals and chemicals that are unique to PV panels and valuable for their recovery from solar panels

(Interviewees 1, 2, 3, 4, 5, 6). There is a discrepancy in efficiency, leading to missed chances to retrieve these precious resources. While the technology required to recycle solar panels exists in India, it faces some significant challenges in terms of delivery and cost. Establishing a large-scale recycling plant for PV materials is a costly endeavor, particularly due to the high implementation costs of associated processing technologies. Accordingly, the financial investment required to develop and operate specialized recycling facilities is high, making it difficult to attract private sector investment as the economic returns from such ventures are not compelling at the moment (Interviewees 2, 4, 5, 6 for implementation issues; Interviewees 3, 4, 5, 6 for affordability concerns). Accordingly, the financial investment to develop and operate specialized recycling facilities is high, making it difficult to attract private sector investment as the economic returns from such ventures are not compelling at the moment (Interviewees 2, 3, 4, 5, 6).

Despite all the odds, there are a few initiatives taken by the private sector regarding solar panel recycling, though it is presently small scale and more or less centred in the southern part of India (Interviewees 1, 2, 3, 4, 5, 6). The need for more significant investment in the infrastructure for solar panel recycling is patently clear. Positive developments are required to create conducive frameworks that make investments in specialised recycling facilities as attractive as those in e-waste management facilities, where smartphones and laptops account for the vast majority of products handled (Interviewees 2, 3, 4, 6). The most positive development is the setting up of an in-house recycling facility by a major US-based company that happens to be a world leader in recycling. The company is building this facility alongside its solar manufacturing facility in India, demonstrating the easy integration of recycling processes within manufacturing operations (Interviewee 3). Furthermore, manufacturers and recyclers are now realizing the importance of partnerships in developing a more integrated and efficient recycling infrastructure. Better technology and cost efficiency can foster such cooperations, resulting in a more streamlined operation of the recycling process (Interviewees 2, 4, 6).

Therefore, this block can be considered partially complete as there are few facilities present for recycling, be it on a small scale or the e-waste management facilities for efficient disposal.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *Lack of dedicated recycling facilities for PV waste (Interviewees 1, 2, 3, 4, 5, 6).*
  Influencing conditions for the identified barriers
  - *Knowledge and Awareness of Technology:*

    A significant influencing factor for the lack of dedicated recycling facilities is the limited knowledge and awareness of the specialised technologies required for PV panel recycling. While the technology exists, its implementation is challenging due to the lack of widespread understanding and expertise in these advanced methods (Interviewees 1, 2, 3, 4, 5, 6). This technological knowledge gap results in underutilization of available technologies, leading to inefficiencies in the recycling process. Facilities that primarily handle e-waste, including smartphones and laptops, lack the necessary technology to effectively process solar panels, leading to missed opportunities for material recovery (Interviewees 1, 2, 3, 4, 5, 6).

– *Natural, Human, and Financial Resources:*

  Establishing specialized recycling facilities necessitates substantial financial investment, which is a significant barrier in terms of natural, human, and financial resources. The high costs associated with setting up these facilities, including advanced technology and infrastructure, make it difficult to attract private sector investment. The economic returns from such ventures are currently not compelling enough to justify the substantial initial outlay (Interviewees 2, 3, 4, 5, 6). Additionally, the lack of skilled human resources trained in the specific technologies and processes required for efficient PV recycling further exacerbates this barrier as the industry struggles to find and develop the necessary talent (Interviewees 3, 4, 5).

– *Macro-economic and Strategic Aspects:*

  From a macro-economic and strategic perspective, the absence of dedicated facilities reflects broader strategic challenges. There is a need for supportive frameworks and policies that make investments in specialized recycling facilities as appealing as those in e-waste management facilities. Current economic conditions and strategic priorities do not favour the development of such specialised infrastructure, leading to a gap in the market that hinders the scaling up of PV recycling operations (Interviewees 2, 3, 4, 6). A major US-based company established an in-house recycling facility alongside its solar manufacturing facility in India, demonstrating the potential for integrating recycling processes directly within manufacturing operations, but such initiatives remain isolated rather than industry-wide practices (Interviewee 3).

– *Knowledge and Awareness of Application and Market:*

  Another factor is a lack of awareness of the application and market potential for recycled PV materials. Stakeholders may not fully understand the economic and environmental benefits of investing in specialised recycling facilities. This lack of market knowledge can lead to hesitancy in committing resources towards developing these facilities, further hindering the growth of the recycling industry (Interviewees 1, 2, 3, 4, 5, 6).

Niche Strategies

– *Hybridization or adaptor niche strategy:*

  Utilizing existing e-waste facilities and adapting them with new technologies for PV recycling can be a practical approach to overcoming the barrier of lacking dedicated facilities. By modifying the current e-waste management infrastructure, the industry can handle PV waste more efficiently, similar to how automotive recycling facilities have adapted to handle new types of batteries.

– *Dedicated System or Standalone Niche Strategy:*

  Developing specialised recycling facilities can address this barrier. This strategy focuses on creating independent systems dedicated to recycling PV waste, ensuring proper handling and processing.

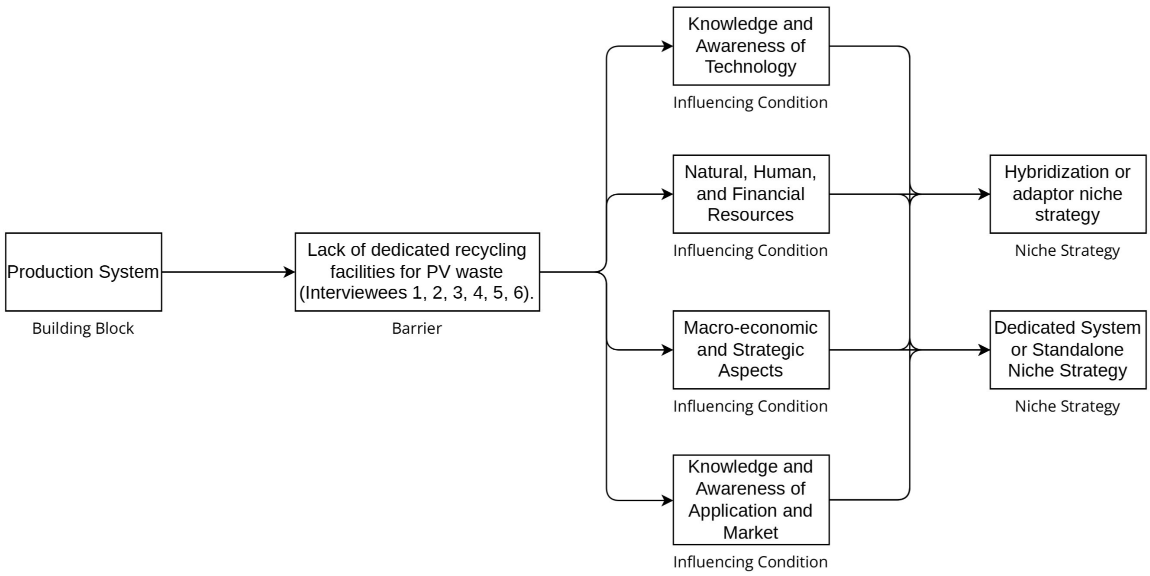

Figure 4.3: Analysis of Production System

4.1.4. Complementary Products and Services:

Interviewees 2, 3, 4, 5, and 6 attribute the largely ineffective implementation of Extended Producer Responsibility (EPR) in India to weak enforcement mechanisms and a lack of stringent regulatory frameworks. Although there is an EPR scheme in place, it differs significantly from the more robust systems found in Europe. Manufacturers can exchange their scrapped products with EPR vendors under the existing scheme, effectively exchanging old products for new ones (Interviewee 1). However, the EPR guidelines outlined by the Ministry of Environment, Forestry, and Climate Change are less comprehensive, primarily requiring manufacturers to register on a portal and submit annual returns without stringent obligations for recycling or refurbishing (Interviewee 3). Additionally, there is considerable reluctance among manufacturers to fully engage with the principles of EPR. This hesitation is often due to the high costs and operational complexities associated with setting up systems for product take-back, recycling, or refurbishment (Interviewees 4, 5, 6). A general lack of consumer awareness about the availability and benefits of repair and take-back services further compounds this lack of commitment. As a result, both consumers and businesses frequently opt for purchasing new products rather than choosing to repair or refurbish existing ones, leading to increased waste and missed opportunities for extending the lifecycle of products (Interviewees 1, 3, 4, 5).

As a result, this block can be considered partially complete because companies provide repair and take-back services, but the implementation of EPR has been unsuccessful. The need for stronger regulatory frameworks and better enforcement of EPR principles is evident. Moreover, enhancing consumer awareness and incentivising manufacturers to participate more actively in EPR schemes could play crucial roles in reducing waste and promoting a more sustainable approach to product lifecycle management.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *Ineffective implementation of Extended Producer Responsibility (EPR) (Interviewees 1, 2, 3, 4, 6).*

  Influencing conditions for the identified barriers

  - *Knowledge and Awareness of Technology:*

    One critical influencing factor is a lack of knowledge and awareness regarding the technological aspects of EPR implementation. Many manufacturers are hesitant to engage fully with EPR principles due to the high costs and operational complexities associated with setting up systems for take-back, recycling, or refurbishing products (Interviewees 4, 5, 6). Reluctance to commit to EPR schemes stems from a lack of widespread understanding or adoption of the technology required to efficiently manage these processes. This technological gap means that companies are often unprepared to handle the logistics and operational demands of effective EPR implementation, resulting in ineffective practices.

  - *Knowledge and Awareness of Application and Market:*

    Another influencing factor is a lack of knowledge and awareness about EPR's application and market benefits. There is a general lack of consumer awareness regarding the availability and benefits of repair and take-back services, which significantly contributes to increased waste (Interviewees 1, 3, 4, 5). Consumers and businesses frequently opt to purchase new products rather than repair or refurbish existing ones, missing opportunities to extend product lifecycles. This lack of awareness hinders the market acceptance of recycled or refurbished products, affecting the overall success of EPR initiatives.

  - *Natural, Human, and Financial Resources:*

    The availability of natural, human, and financial resources also plays a crucial role in the ineffective implementation of EPR. The high costs associated with establishing and maintaining EPR systems, including the necessary technological infrastructure and skilled personnel, are substantial barriers (Interviewees 2, 3, 4, 5, 6). Without adequate financial incentives or subsidies from the government, companies find it challenging to allocate the necessary resources to develop effective EPR systems. Additionally, the lack of skilled human resources trained in the specific processes and technologies required for EPR further complicates the implementation (Interviewees 3, 4, 5).

– *Macro-economic and Strategic Aspects:*

  The absence of a regulatory framework and strategic leadership further hinders effective implementation of EPR from a macro-economic and strategic perspective. The current guidelines are insufficiently comprehensive, primarily requiring registration and annual returns without stringent recycling obligations (Interviewee 3). This regulatory ambiguity discourages investment in EPR infrastructure and practices, as companies are uncertain about compliance requirements and the long-term viability of their investments. Stronger regulatory frameworks and better enforcement of EPR principles are necessary to provide the strategic direction and stability needed for successful implementation (Interviewees 2, 3, 4, 5, 6).

Niche Strategies

– *Educate niche strategy:*

  Aiming to increase knowledge and awareness among manufacturers and consumers about the benefits and implementation of EPR can foster better engagement and compliance. Similar to the recycling of plastic bottles, education campaigns can inform stakeholders about the benefits and legal requirements of EPR.

– *Hybridization or Adaptor Niche Strategy:*

  Utilizing existing infrastructure and integrating new recycling processes with current systems can improve EPR implementation. This strategy helps in ensuring that complementary products and services work well together, facilitating a smoother recycling process.

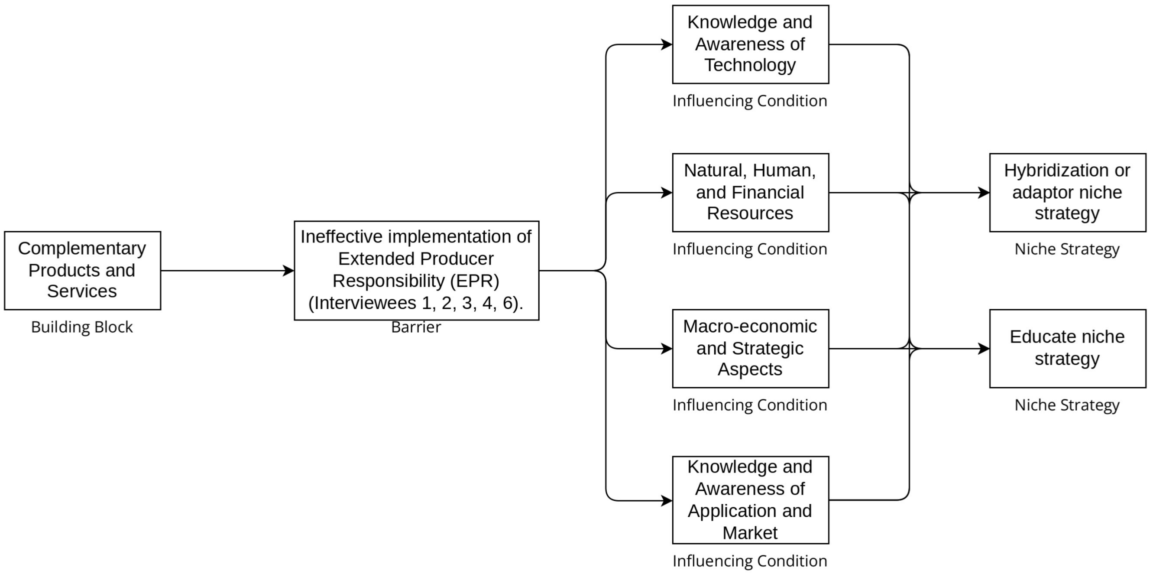

Figure 4.4: Analysis of Complementary Products and Services

4.1.5. Network Formation and Coordination

The solar industry and the government have agreed on the need to develop a systematic approach to collect and recycle solar panels, yet they have not finalised any concrete plans. Despite various policy recommendations from the Ministry of New and Renewable Energy, practical implementation has remained problematic due to various issues that arose during the policy's application (Interviewees 1, 2, 3, 4, 5, 6). Additionally, PVcycle Europe and the National Solar Energy Federation of India (NSEFI) have initiated collaborations to shape solar recycling policies within India, with the aim of introducing readily adoptable strategies (Interviewee 3). Within the industry, there are expectations for the government to establish demonstration recycling facilities and collection centers that take economic, logistical, regulatory, and structural factors into account. The government could use this as a model to manage recycling more effectively across the country (Interviewees 1, 4, 5). Moreover, there is a recognised effort from the government to engage with all relevant stakeholders to develop easily implementable policies, especially since past recommendations have proven too complex to put into practice effectively (Interviewees 1, 2, 3, 4, 5, 6).

However, a significant challenge has been the lack of proactive leadership from both the government and the industry. The government, through the Ministry of New and Renewable Energy, has historically driven initiatives like launching the solar mission, subsidising solar installations, and officially registering solar installations. This implies that, when it comes to recycling, the government must take the lead, as the private sector can only comply with regulations instead of innovating them. We deem subsidies and financial incentives necessary to offset the initial costs of establishing recycling facilities; otherwise, consumers may bear the burden of these costs, potentially discouraging the adoption of recycling practices (Interviewee

2). Furthermore, there is a notable reluctance among stakeholders to fully commit to recycling initiatives due to concerns about the costs versus the benefits and the logistical challenges involved. These factors make it difficult to establish effective partnerships that are crucial for advancing recycling efforts in the solar industry (Interviewees 1, 3, 5).

Therefore, this block can be considered partially complete because even if there aren't any concrete policies yet in place, we see collaboration between stakeholders to form something concrete, and there is a mutual understanding between the stakeholders that they need to form a network and formulate something concrete. So there is no reluctance. The development of a robust recycling infrastructure for solar panels in India is crucial, but it requires coordinated efforts, clear leadership, and supportive policies to overcome the current barriers and ensure long-term sustainability and effectiveness.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *Lack of concrete structure to policies clarity on how to implement the policies (Interviewees 1, 2, 3, 4, 5, 6).*

  Influencing conditions for the identified barriers

  - *Knowledge and Awareness of Technology:*

    A critical influencing condition for the lack of a concrete policy structure and implementation clarity is the insufficient knowledge and awareness of the technological aspects of solar panel recycling among policymakers. Effective recycling policies require a deep understanding of the technologies involved in collecting, processing, and recycling solar panels. Without this knowledge, the development of clear and actionable policies becomes challenging, leading to ambiguities that hinder effective implementation (Interviewees 1, 2, 3, 4, 5, 6).

  - *Knowledge and Awareness of Application and Market:*

    Additionally, there is a deficiency in a comprehensive understanding of the appropriate application of recycling processes within the market context. Policymakers and industry stakeholders need detailed insights into market dynamics, including the economic viability of recycling materials and the logistical requirements of managing end-of-life panels. According to Interviewees 1, 2, 3, 4, 5, 6, this gap in market knowledge can result in policy recommendations that do not fully align with practical realities, thereby complicating their implementation.

  - *Macro-economic and Strategic Aspects:*

    From a macro-economic and strategic perspective, the absence of a well-defined policy framework reflects broader strategic challenges. Clear and structured policies are crucial for providing a stable and predictable environment that encourages investment and coordination among stakeholders. The lack of clarity in policy structure and implementation guidelines creates uncertainty, which can deter investment and participation from both the private sector and governmental bodies (Interviewees 1, 2, 3, 4, 5, 6). This strategic ambiguity complicates the establishment of a cohesive and efficient recycling infrastructure.

- *Lack of government leadership and initiatives (Interviewees 1, 2, 3, 4, 5, 6).*

  Influencing conditions for the identified barriers

  - *Macro-economic and Strategic Aspects:*

    Macro-economic and strategic aspects significantly influence the government's lack of proactive leadership. Strong government leadership has historically driven successful initiatives in the solar sector, including the launch of the solar mission and subsidies for solar installations. In the realm of recycling, similar leadership is necessary to drive policy development, provide financial incentives, and establish demonstration recycling facilities. Without government-led initiatives, the private sector lacks the regulatory framework and strategic direction needed to develop and implement effective recycling practices (Interviewees 1, 2, 3, 4, 5, 6).

  - *Natural, Human, and Financial Resources:*

    Government leadership is also crucial for mobilising the natural, human, and financial resources needed to support the recycling industry. Establishing recycling facilities and creating an efficient collection and logistics network require substantial investment. Government subsidies and financial incentives are essential to offset the high initial costs and operational expenses associated with these developments. Without such support, the financial burden may fall on consumers, discouraging the adoption of recycling practices (Interviewee 2).

  - *Knowledge and Awareness of Technology:*

    Effective government initiatives also require a deep understanding of the technological requirements for solar panel recycling. Policymakers need to be well-informed about the latest advancements and best practices in recycling technologies to develop policies that are both practical and forward-looking. This technological knowledge is essential for crafting policies that can support the long-term sustainability and growth of the recycling industry (Interviewees 1, 2, 3, 4, 5, 6).

  Niche Strategies

  - *Geographic niche strategy:*

    Pilot programs can serve as a model for broader application by implementing them in regions with more favorable conditions or where policy implementation is easier to manage. Start with states that possess robust environmental regulations and infrastructure.

  - *Networking and lobbying strategy:*

Engaging in strategic alliances and lobbying for clearer policies and government support can help establish a more coordinated approach to recycling. This strategy involves building coalitions of stakeholders to advocate for necessary policy changes, similar to how renewable energy coalitions work to influence energy policies.

– *Lead User Niche Strategy:*

Engaging innovators and lead users can provide valuable feedback and co-develop solutions for policy implementation. This strategy encourages collaboration and helps in forming a clear and effective structure for recycling policies.

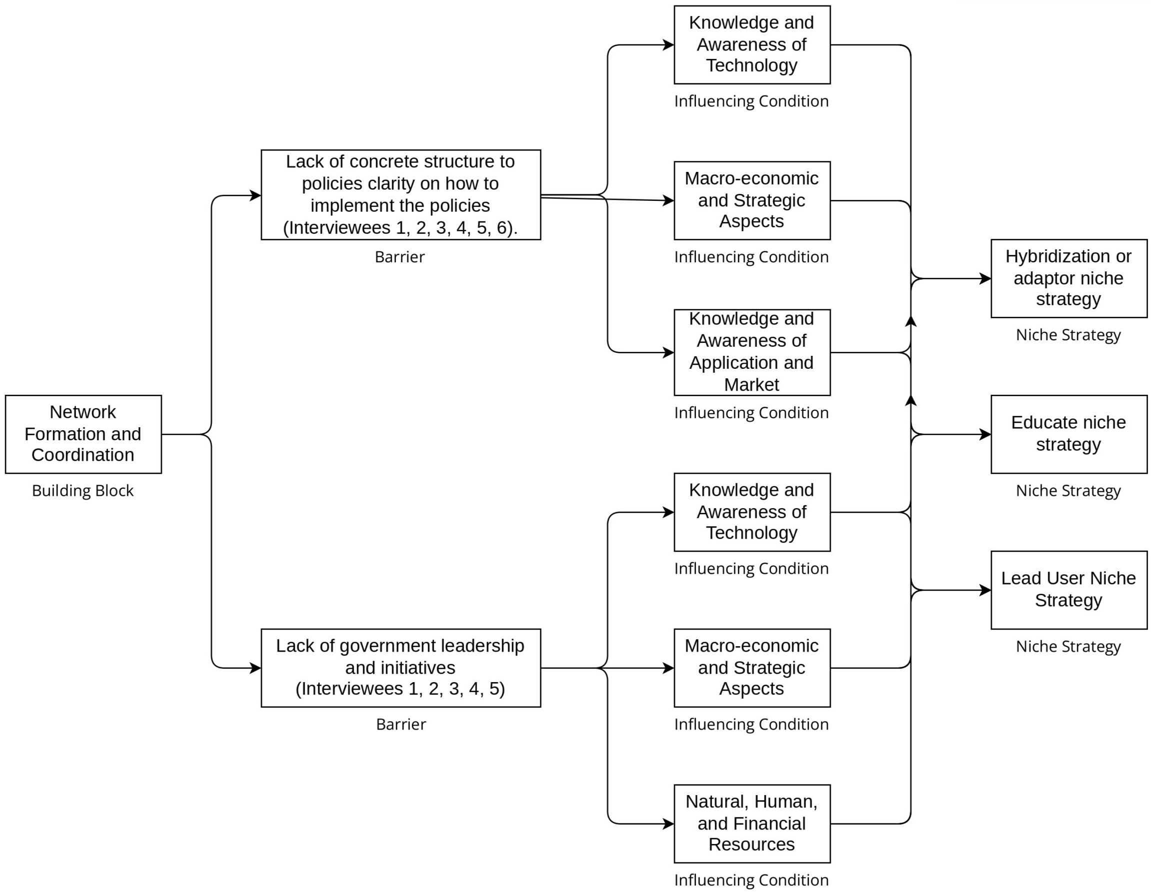

Figure 4.5: Analysis of Network Formation and Coordination

4.1.6. Customers

This building block basically deals with customer awareness, acceptance, customer ownership preferences, and resistance to change. The above is not applicable in this case, mainly because of the recycled materials and their application post recycling within the context of PV recycling in India. The recycled materials from end-of-life (EoL) PV panels, such as silicon, aluminum, glass, and other metals, are generally sold as raw materials for various industrial applications. These materials are not introduced back into the same PV manufacturing sequence but are used in different industries altogether. For instance, one can reprocess silicon to produce other industrial parts or non-PV electronics. Smelting aluminum and glass materials allows for their reuse in a wide range of products, ranging from construction to consumer goods.

Since the recycled materials are not used in the actual production of PV panels, it does not directly affect the general customer base that purchases solar panels from companies. Thus, acceptance, awareness of recycled products, frictions to using recycled materials, and the addressing of end consumers are all the usual problems associated with the building block customers and are not relevant. The markets for recycled PV panel materials differ significantly from the consumer markets for the final solar panels. Industries purchase raw materials in large quantities for various fabrication processes, dominating these markets. These industries are less concerned with the origins of the materials (whether they are recycled or virgin) and more with the quality and price. As a result, the focus shifts away from individual consumer preferences to the broader dynamics of industrial material supply chains.

On the other hand, while customers may not be a significant building block in this phase, they may gain significance in the future, particularly as the concepts of the circular economy begin to gain traction. Indeed, as the circular economy really takes off, the 9Rs could find broader application: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle. If the PV industry in India moves towards a model where recycled materials are reintegrated into the production of new PV panels or other consumer products, customer awareness and acceptance might become crucial. In such a scenario, consumers would need to be educated about the benefits of recycled content in new PV panels or other products, and their preferences would play a role in market dynamics.

4.1.7. Innovation-specific Institutions:

The lack of specific standards and norms tailored for solar panel recycling is a significant challenge that all interviewees (1, 2, 3, 4, 5, 6) agree hampers the establishment of effective recycling practices. Currently, the absence of such standards leads to inconsistent and inefficient recycling processes. This inconsistency impedes the development of universally accepted practices and technologies, which are critical for the recycling industry's advancement. Additionally, the regulatory response to the recycling industry's needs has been slow, and existing regulations often lack clarity, complicating the implementation of effective recycling technologies (Interviewees 1, 2, 4, 5, 6). This lack of clear regulations creates uncertainty for potential investments, particularly in research and development. Investors are understandably hesitant to commit funds when there is uncertainty about regulatory compliance and the potential for future changes in the law.

However, there is potential for progress in the sector. Interviewees (1, 2, 3, 4, 5, 6) have underscored the potential for the development of new institutions or frameworks specifically tailored to support the recycling industry. Such developments could include the creation of dedicated collection centres and separation facilities. These facilities would not only adhere to specific recycling standards but also work closely with the industry to innovate and improve current recycling technologies. By collaborating directly with industry leaders, these institutions could help propel the recycling sector forward, making it more efficient and effective. In summary, while the recycling of solar panels faces significant hurdles due to the lack of specific regulatory standards and the slow pace of governmental response, there is a clear path forward. By establishing dedicated institutions and fostering close collaborations between these institutions and the industry, there is a strong potential to overcome current barriers and significantly enhance the efficiency and efficacy of recycling practices within the sector.

Therefore this building block can be considered as incomplete.

Barriers, Influencing Conditions and Niche Strategies
Barriers identified

- *Need for specialized institutions and norms for PV panel recycling (Interviewees 1, 2, 3, 5).*

  Influencing conditions for the identified barriers

  – *Knowledge and Awareness of Technology:*

    One of the critical influencing conditions is a lack of knowledge and awareness of the technology required to develop and enforce specific standards and norms for PV panel recycling. The lack of clear and consistent technological guidelines causes inefficiencies in recycling processes, as different facilities may adopt varying methods that lack standardization or optimization (Interviewees 1, 2, 3, 4, 5, 6). This lack of standardised technological knowledge hinders the establishment of best practices that could improve the overall efficiency and effectiveness of recycling operations.

  – *Knowledge and Awareness of Application and Market:*

    The knowledge and awareness gap regarding the application and market potential for recycled PV materials also plays a significant role. Stakeholders need to understand the economic and environmental benefits of implementing specific standards and norms. Without this understanding, there is little motivation to invest in developing the necessary institutional frameworks that can support standardised recycling practices (Interviewees 1, 2, 3, 4, 5, 6). A well-informed market perspective can drive the adoption of norms that align with both industry needs and environmental goals.

  – *Macro-economic and Strategic Aspects:*

From a macro-economic and strategic perspective, the lack of specific standards and norms reflects broader challenges in the strategic planning and regulatory framework. Clear and detailed standards are crucial for providing a stable and predictable environment that encourages investment in recycling technologies and infrastructure. The absence of such standards creates uncertainty, which can deter investments in research and development necessary to innovate and improve recycling technologies (Interviewees 1, 2, 4, 5, 6). Strategic regulatory frameworks that clearly define recycling processes and compliance requirements are essential for fostering a robust and effective recycling industry.

– *Natural, Human, and Financial Resources:*

  Establishing specialised institutions and developing norms require substantial natural, human, and financial resources. The creation of dedicated collection centres and separation facilities involves significant investment, and without adequate financial resources or incentives, these initiatives may not materialise (Interviewees 2, 3, 4, 5, 6). Additionally, the development and enforcement of these standards necessitate skilled human resources who are knowledgeable about the latest technologies and best practices in recycling. The availability of such resources is critical for the successful implementation of standardised recycling processes.

– *Competition:*

  In a competitive market, the establishment of standardised norms can also drive innovation and efficiency. Companies that adhere to these standards can gain a competitive edge by demonstrating compliance with high-quality recycling practices. This competitive aspect can motivate companies to invest in the necessary technologies and processes to meet these standards, thereby enhancing the overall effectiveness of the recycling industry (Interviewees 1, 2, 3, 4, 5, 6).

Niche Strategies

– *Dedicated system or stand-alone niche strategy:*

  Developing dedicated institutions and frameworks for PV panel recycling can effectively address the gap and support the industry. Similar to how specialised research institutes for renewable energy have driven technological advancements in that field, dedicated PV recycling institutions can drive innovation and standardisation.

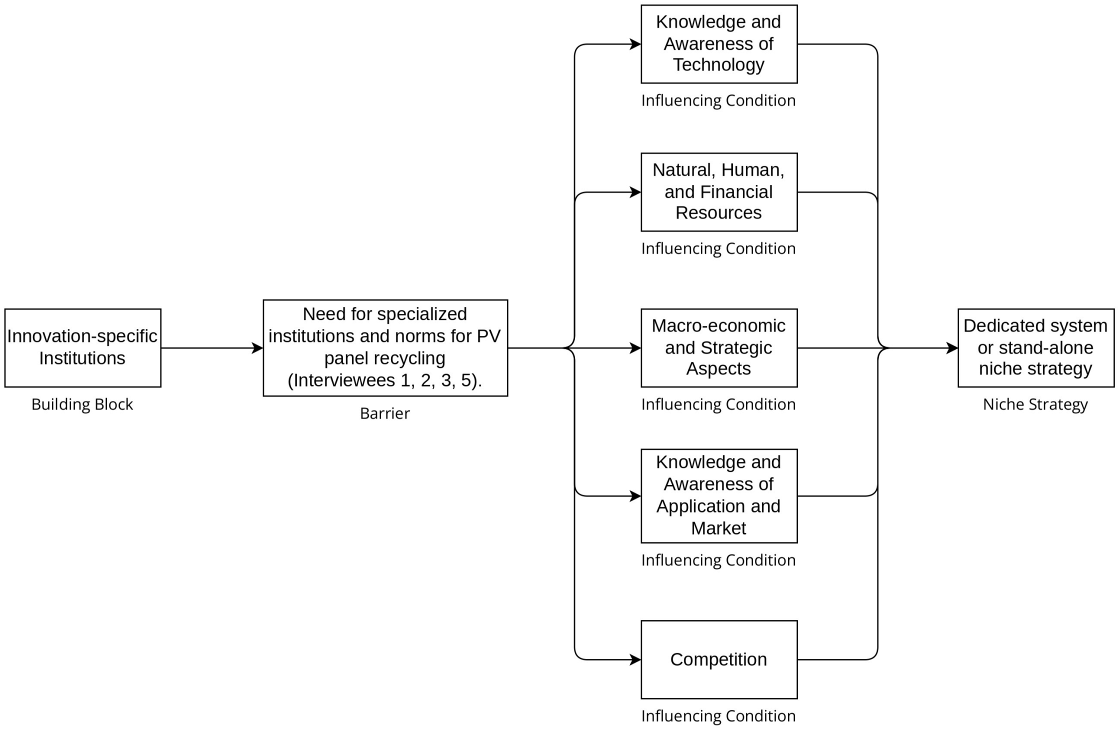

Figure 4.6: Analysis of Innovation-specific Institutions

4.1.8. Reverse Logistics:

The recycling process for end-of-life (EoL) solar panels faces significant inefficiencies due to the lack of a formal logistic route for their collection and sorting, a concern voiced by all interviewees (1, 2, 3, 4, 5, 6). The absence of a structured approach not only complicates the recycling process but also results in missed opportunities to recover valuable materials. An inadequate logistical infrastructure, which fails to support efficient transportation and sorting of waste materials, exacerbates this inefficiency. Further exacerbating the issue is the current system's inability to efficiently manage the logistics involved in recycling. Without an infrastructure to support the movement and processing of discarded panels, the entire recycling endeavour becomes less effective and more costly. Interviewees (1, 2, 3, 4, 5, 6) stress the critical need for a well-defined system that can handle these tasks with greater efficiency.

To address these challenges, some interviewees (1, 4) suggest that forming partnerships between manufacturers, recyclers, and logistics companies could be a transformative step towards optimising the recycling process. By collaborating, these stakeholders can develop more streamlined and cost-effective logistic routes, which would not only enhance the efficiency of recycling but also reduce the overall costs associated with these processes. Moreover, there is a strong call for governmental involvement to bolster these efforts. Interviewees (1, 2, 3, 4, 5, 6) highlight the potential benefits of regulatory incentives and government support in enhancing the reverse logistics infrastructure. By implementing policies that encourage or even mandate the development of dedicated logistic systems specifically designed for solar panel recycling, the government could play a pivotal role in overcoming the existing barriers. Such support would not only facilitate the establishment of necessary infrastructure, but also ensure that the recycling process becomes more viable and effective in the long run.

This building block can be considered incomplete. In summary, the development of a more robust and structured logistic system for solar panel recycling is essential. The combined efforts of industry stakeholders, supported by appropriate governmental policies and incentives, could significantly improve the efficiency and effectiveness of recycling practices, ultimately leading to better material recovery and reduced environmental impact.

Barriers, Influencing Conditions and Niche Strategies

Barriers identified

- *Absence of structured collection and sorting facilities (Interviewees 1, 2, 3, 4, 5, 6).*

  Influencing conditions for the identified barriers

  - *Knowledge and Awareness of Technology:*

    One significant influencing factor is a lack of knowledge and awareness of advanced technologies that could facilitate the establishment of structured collection and sorting facilities. Efficient recycling of solar panels requires specific technologies for identifying, sorting, and processing different materials. The absence of such technological knowledge among stakeholders results in inefficient collection and sorting processes, which are critical steps in the recycling chain (Interviewees 1, 2, 3, 4, 5, 6). The lack of standardised technological solutions contributes to the inefficiency of the recycling process, as different regions and facilities may adopt varying methods that are not optimised for solar panel recycling.

  - *Knowledge and Awareness of Application and Market:*

    Another influencing factor is a lack of knowledge and awareness of the application and market dynamics for recycled solar panel materials. Stakeholders need to understand the economic benefits and market opportunities for recovered materials to justify the investment in structured collection and sorting facilities. The lack of market knowledge can lead to hesitation in developing the necessary infrastructure, as the economic returns may seem uncertain or unconvincing (Interviewees 1, 2, 3, 4, 5, 6). A better understanding of market demands and potential applications for recycled materials could drive more targeted investments in logistics infrastructure.

  - *Macro-economic and Strategic Aspects:*

    From a macro-economic and strategic perspective, the absence of structured facilities reflects broader strategic challenges. Clear and organised logistic systems are essential for providing a stable and predictable environment that encourages investment and coordination among stakeholders. The lack of clarity in logistical frameworks and the absence of strategic planning create uncertainty, deterring investments in the necessary infrastructure to support efficient recycling processes (Interviewees 1, 2, 3, 4, 5, 6). Establishing clear and standardised logistical frameworks is crucial for fostering a robust recycling industry.

- *Collaboration of stakeholders for streamlined logistics (Interviewees 1, 2, 3, 4).*

  Influencing conditions for the identified barriers

  – *Knowledge and Awareness of Technology:*

  Knowledge and awareness of the technological solutions available for efficient logistics management influence the collaboration of various stakeholders to streamline logistics. To optimize the recycling process, effective collaboration necessitates the integration of advanced data management systems and logistics technologies. The lack of awareness and adoption of such technologies among stakeholders hampers the development of efficient logistic routes and coordination mechanisms (Interviewees 1, 2, 3, 4, 5, 6).

  – *Macro-economic and Strategic Aspects:*

  Strategically, stakeholder collaboration is essential for developing a cohesive and efficient logistics network. The absence of proactive collaboration efforts results in fragmented and inefficient recycling operations. Clear strategic leadership and supportive policies are necessary to foster collaboration between manufacturers, recyclers, and logistics companies. Such partnerships can lead to more streamlined and cost-effective logistic routes, enhancing the overall efficiency of the recycling process (Interviewees 1, 3, 5).

  – *Natural, Human, and Financial Resources:*

  Effective collaboration also requires adequate natural, human, and financial resources. Establishing partnerships and integrating logistics systems involve significant financial investments and skilled human resources to manage the complex logistics operations. Without sufficient resources, it is challenging to create and maintain efficient logistical networks. Government support, in the form of subsidies and incentives, can play a pivotal role in facilitating these collaborations by providing the necessary financial backing and encouraging stakeholder engagement (Interviewees 1, 2, 3, 4, 5, 6).

  Niche Strategies

  – *Hybridization or adaptor niche strategy:*

  Adapting existing logistical infrastructure to better handle the unique requirements of PV panel recycling can improve efficiency and effectiveness. By integrating reverse logistics into existing supply chains, similar to how retailers manage product returns, the recycling process can become more streamlined and cost-effective.

  – *Networking and lobbying strategy:*

Building partnerships between manufacturers, recyclers, and logistics companies can enhance the efficiency of reverse logistics. By fostering collaboration and leveraging shared resources, stakeholders can develop a cohesive and efficient logistics network. This strategy also involves advocating for regulatory support and incentives to facilitate these collaborations.

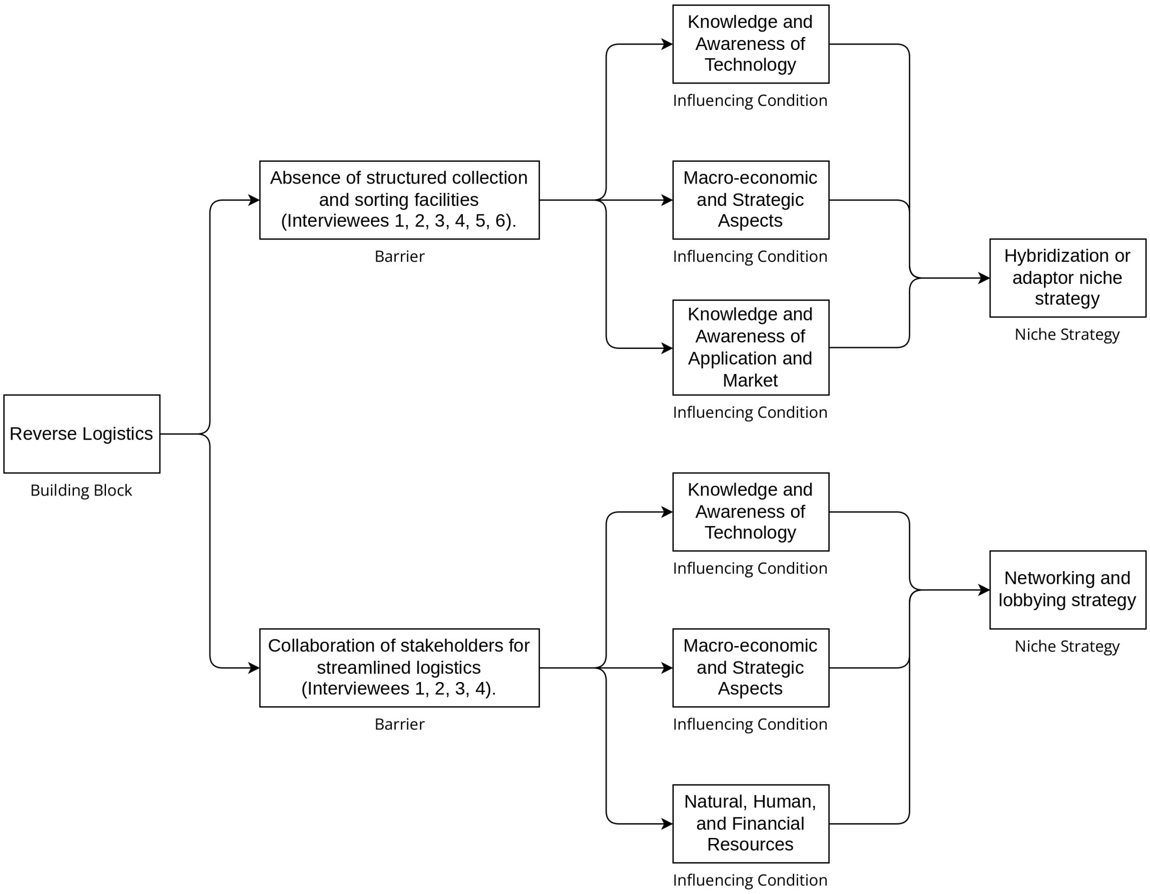

Figure 4.7: Analysis of Reverse Logistics

4.2. Adaptation of framework for Circular Innovation of PV Panel in India

This section adapts the TIS Framework to the case of PV panel recycling in India. The combined framework in figure 2.7 and figure 2.8 is used as the starting point, and its indicators are modified further for my case in figure 4.8 and figure 4.9. The modifications are made in the form of indicators. Highlighted the indicators not relevant to my case in Red, added indicators suggested as additions are in Green, and slightly modified the relevant indicators in Violet. The reasons for additions, exclusions and modifications are mentioned in the last column of both figures.

Building Blocks	Combined Indicators	Reason for Exclusion/Modification
Product Performance and Quality	- Design for circularity - Resource optimisation - Integrated PSS - Local Recycling Technology - Material Recovery Efficiency - Quality of recycled materials	Design for circularity and integrated PSS are more relevant to manufacturing, while local recycling technology and material recovery efficiency address current technological gaps in PV panel recycling in India.
Product Price	- Long term feasibility - Total cost of ownership - Price disparity - Circular vs linear price - Extended ROI - Business case challenge - Economic Viability of Recycling - Market Pricing for Recycled Materials - Availability of Incentives and Subsidies	Long term feasibility, total cost of ownership, circular vs linear price, and extended ROI are encompassed within economic viability and market pricing, making the indicators more specific to the context of India.
Production System	- 9 R(s) capability - Strong reverse logistics - Flexibility & Adaptability - Economies of scale - Dedicated Recycling Facilities - Integration with Existing Infrastructure	Flexibility and adaptability are a part of integration with existing infrastructure as it is more relevant for now. 9 R(s) are less immediate concerns for now.
Complementary Products and Services	- Collaboration - Ecosystem of products/services - Industry specific infrastructure - Implementation and Effectiveness of EPR	Ecosystem of products/services is too broad and is better addressed by focusing specifically on the effective implementation of EPR in India. While collaboration and industry specific infrastructure are covered in other building blocks.
Network Formation and Coordination	- Strong network - Division of responsibility - Shared goals - Collaboration reluctance - Network formation - Convincing partners - Standards absent - Third-party absence - Stakeholder resistance - Collaboration between stakeholders - Development of policy and regulatory support - Establishment of demonstration projects	
Customers	- Awareness & knowledge - Ownership preferences - Resistance to change - Customer acceptance - Reaching customers	This building block is not relevant for now as all the recycled materials are sold as new raw materials for different applications other than solar. But in future it is relevant considering the broader scope or 9Rs
Innovation-specific Institutions	- Standardisation - Regulation clarity - General Consensus - Emerging robust policies - Legislation inconsistency - Material classification - Health & safety - Specialized institutions for CI - Enforcement of standards and norms - R&D in recycling technologies	Health & Safety isn't exactly relevant for PV panel recycling process. Robust policies are being developed but implantation of those remains a challenge. Legislation inconsistency is a major problem as state level governments and central level governments enforce different rules. Broad institutional indicators are specified to focus on the creation of specialized institutions, enforcement of standards, and regulatory clarity for India.
Reverse Logistics	- Recycling infrastructure - Reverse logistics - Recycling systems - Circular infrastructure - Integration existing supply chains	

Figure 4.8: Building Blocks for PV Recycling

Influencing Conditions	Combined Indicators (Raghav's and Jules')	Reason for Exclusion
Knowledge and Awareness of Technology	- Limited scope of circular products - Large scale demonstration - Design limitations - Concept validation - Product & Technology Limitations - Awareness of available technologies	Recycled materials sold as new. Design limitations are less critical compared to technology limitations in PV recycling. Large-scale demonstrations are less feasible due to high costs and infrastructural constraints in India.
Knowledge and Awareness of Application and Market	- Uncertain returns - Linear lock-ins - Asymmetric information - Knowledge gap - Sector knowledge - Impact data	
Natural, Human and Financial Resources	- Resource flow optimization - Leadership & team skills - Availability of finances - Supply limitations - Capital access - Flow inconsistency	
Competition	- Market positioning - Conventional competition - Value proposition - Material competition - Technology variety - Regulatory strain	
Macro-Economic and Strategic Aspects	- Systemic perspective - Economic conditions - Conductive regulations - Policy support - Tax bias - Raw material bias - CE criteria absence	Tax & Raw Material biases are less prominent in the PV Panel Recycling in India. Covered under policy support and clarity.
Socio-Cultural Aspects	- Literacy & motivation - Informed preferences - Limited information & knowledge - Value chain inequality - Counterproductive behavior - Sustainable disinterest - Business inertia - Process confusion - Reputation risk - Repair limitations	General awareness and literacy are more critical. Less relevant due to the focus on recycling, not repair. Covered under limited information and knowledge. Less significant compared to other socio-cultural aspects.
Accidents and Events	- Internal disruption - Cascading effects - Resilience	Less relevant due to the current status of PV panel recycling in India.
Data Infrastructure	- Tracking difficulties	

Figure 4.9: Influencing Conditions for PV Recycling

4.2.1. Product Performance and Quality

- **Local Recycling Technology:** The current recycling technologies in India are not sufficiently advanced to handle the specific requirements of PV panel materials, particularly silicon wrapped in EVA lamination. This results in reduced purity and usability of the recovered silicon, presenting a significant barrier to effective recycling (Interviewees 1, 2, 3, 4, 5, 6). The quality of recycled materials varies significantly depending on the recycler and the recycling process used (Interviewees 1, 2, 5). Ensuring that recycled materials meet industry standards is essential for their acceptance in the market. Improvements in recycling technology are essential to increasing the efficiency and quality of material recovery. For instance, better separation techniques could help in reclaiming high-purity silicon, making the recycling process more viable and economically attractive.

- **Material recovery efficiency:** Efficiency in material recovery is critical for recycling operations' economic viability. The low recovery rates for valuable materials like silver and copper further complicate the process (Interviewee 4, 5). Advanced technologies that can improve the extraction and purity of these materials are necessary to enhance the overall efficiency of the recycling process. By ensuring efficient recovery, we can extract the maximum value from EoL panels, thereby supporting the economic rationale for recycling.
- **Quality of recycled materials:** The efficiency of the recycling process directly influences the quality of recycled materials. Competitive prices for high-quality recycled materials make the recycling process economically viable. The quality of recycled materials varies significantly depending on the recycler and the recycling process used (Interviewees 1, 2, 5). Ensuring that recycled materials meet industry standards is essential for their acceptance in the market.
- **Design for Circularity, Integrated PSS, Resource Optimization:** These indicators were removed because of their focus more on manufacturing rather than recycling, as they are more relevant during the production phase of PV panels.

4.2.2. Product Price

- **Economic viability of recycling various materials:** The economic viability of recycling materials like copper and silver is questionable due to their low presence in individual panels (Interviewees 1, 2, 3, 4, 5, 6). To make recycling economically viable, it is essential to process large volumes of these materials. Creating a market for recycled materials and providing financial incentives can help achieve the required scale.
- **Market pricing for recycled materials:** To make recycling economically viable, the market price for recycled materials must be competitive with new materials. This requires ensuring the high quality of recycled materials and developing efficient recovery processes. Government policies that support the use of recycled materials can also help stabilise market prices.
- **Availability of financial incentives and subsidies:** Financial incentives and subsidies are crucial for offsetting the high initial setup and operational costs associated with recycling facilities (Interviewees 1, 2, 3, 4, 5, 6). Government support in the form of subsidies can encourage private sector investment and help establish sustainable recycling

infrastructure.

- **Long-Term Feasibility, Total Cost of Ownership, Circular vs. Linear Price, Extended ROI:** These indicators were combined under the broader categories of economic viability and market pricing to make them more relevant to India's present situation. The focus was shifted to ensure that these indicators specifically address the economic challenges faced in Indian PV recycling.

4.2.3. Production System

- **Dedicated recycling facilities:** The absence of dedicated recycling facilities for PV panels is a significant barrier. Despite the existence of several e-waste management facilities, they lack the necessary optimization for PV recycling, according to Interviewees 1, 2, 3, 4, 5, and 6. Establishing dedicated facilities with the necessary technology to handle PV panels can improve the efficiency and effectiveness of recycling operations.
- **Integration with existing infrastructure:** Integrating PV recycling with existing waste management infrastructure can improve efficiency and reduce costs. This integration guarantees the systematic handling of all waste types, thereby fostering a more sustainable approach to waste management.
- **Flexibility & Adaptability, 9 R(s) Capability:** These indicators were removed because they are a part of a broader indicator: Integration with existing and solely focusing on them for now is less concerning

4.2.4. Complementary Products and Services

- **Implementation and effectiveness of EPR:** The implementation of Extended Producer Responsibility (EPR) has been largely ineffective due to weak enforcement mechanisms and a lack of stringent regulatory frameworks (Interviewees 2, 3, 4, 5, 6). Strengthening EPR policies and ensuring effective implementation can significantly improve PV panel recycling.
- **Collaboration, Ecosystem of products/services, Industry specific infrastructure:** The reason of exclusion of these indicators was that Ecosystem of products/services is too broad and is better addressed by focusing specifically on the effective implementation of EPR in India. While collaboration and industry specific infrastructure are covered in other building blocks

4.2.5. Network Formation and Coordination

- **Collaboration between stakeholders:** Effective collaboration between stakeholders is essential for developing a robust recycling infrastructure. This includes the government, industry, and NGOs working together to develop policies and implement recycling programs (Interviewees 1, 2, 3, 4, 5, 6).

- **Development of policy and regulatory support:** Developing clear and supportive policy frameworks is crucial for promoting recycling. These frameworks should provide the necessary regulatory support and incentives to encourage investment in recycling infrastructure (Interviewees 1, 2, 3, 4, 5, 6).
- **Establishment of demonstration projects:** Demonstration projects and pilot programs can help in testing and refining recycling processes. Interviewees 1, 4, and 5 suggest that these projects offer valuable insights and data that can enhance recycling operations and policies.
- **Strong network, Division of responsibility, Shared goals, Collaboration reluctance, Network formation, Convincing partners, Standards absent, Third-party absence, Stakeholder resistance:** These indicators were reframed into 3 new indicators as they are too specific and considering the current stage of PV panel recycling in India is at its nascent stage they new indicators are more suitable.

4.2.6. Innovation-specific Institutions

- **Specialized institutions for circular innovation:** Creating specialised institutions that focus on circular innovation can support the development and implementation of recycling technologies and processes. These institutions can provide the necessary expertise and resources to drive innovation in the recycling sector (Interviewees 1, 2, 3, 4, 5, 6).
- **Enforcement of standards and norms:** Developing and enforcing standards and norms for recycling is crucial for ensuring consistency and quality. Interviewees 1, 2, 4, 5, and 6 recommend aligning these standards with international best practices and adapting them to the local context to ensure their relevance and effectiveness.
- **R&D in recycling technologies:** Supporting research and development in recycling technologies is essential for improving the efficiency and effectiveness of recycling processes. This includes funding for R&D and creating partnerships between research institutions and industry (Interviewees 1, 2, 3, 4, 5, 6).
- **Emerging robust policies, Legislation inconsistency, Material classification :** Robust policies are being developed but implantation of those remains a challenge. Legislation inconsistency is a major problem as state level governments and central level governments enforce different rules. Broad institutional indicators are specified to focus on the creation of specialized institutions, enforcement of standards, and regulatory clarity for India.

4.2.7. Customers

- **Awareness & knowledge, Ownership preferences, Resistance to change, Customer acceptance, Reaching customers:** These indicators are not relevant for now as all the recycled materials are sold as new raw materials for different applications other than solar therefore making the whole building block not relevant for now. But in future it is relevant considering the broader scope or 9Rs

4.2.8. Reverse Logistics

- **Integration with existing supply chains:** Integrating reverse logistics with existing supply chains can improve efficiency and reduce costs. This integration streamlines and aligns the movement of EoL products with other logistic operations (Interviewees 1, 2, 3, 4, 5, 6).

4.2.9. Knowledge and Awareness of Technology

- **Product & Technology Limitations:** One of the major obstacles identified is the technological complexity involved in recycling silicon without degrading its quality. For instance, silicon wrapped in EVA lamination presents significant challenges due to its intricate separation process. This indicates a need for improved knowledge and awareness of recycling technologies specific to PV panels (Interviewees 1, 2, 3, 4, 5, 6).
- **Awareness of Available Technologies:** There is a lack of awareness among stakeholders about the latest advancements in PV panel recycling technologies. For example, many industry players are unaware of cutting-edge methods for efficiently extracting valuable materials like silver and copper. This gap hinders the adoption of advanced recycling processes (Interviewees 2, 4, 5).
- **Limited scope of circular products, Large scale demonstration, Design limitations:** These indicators were excluded because recycled materials are sold as new. Design limitations are less critical compared to technology limitations in PV recycling. Large-scale demonstrations are less feasible due to high costs and infrastructural constraints in India.

4.2.10. Macro-Economic and Strategic Aspects

- **Conductive regulations, Tax bias, Raw material bias:** Tax & Raw Material biases are less prominent in the PV Panel Recycling in India and conductive regulations are covered under policy support and clarity.

4.2.11. Socio-Cultural Aspects

- **Counterproductive behavior, Sustainable disinterest, Business inertia:** General awareness and literacy are more critical and they remain less relevant due to the focus on recycling, not repair. They are covered under limited information and knowledge but remain less significant compared to other socio-cultural aspects.

4.2.12. Accidents and Events

- **Internal disruption, Cascading effects, Resilience:** These were excluded because they remain less relevant due to the current status of PV panel recycling in India.

5
Discussion

This chapter aims to critically analyse the findings of the thesis with respect to the set-out research objectives and questions. The goal of the research was to evaluate drivers and barriers to circular innovation in the Indian photovoltaic sector, specifically in the area of end-of-life photovoltaic panels. Finally, it aimed to suggest some niche strategies that might plausibly overcome the identified barriers and serve as a spur towards circular practices in the industry.

In this chapter, we revisit the main findings on drivers and barriers to circular innovation identified through the application of the TIS framework and substantiated by stakeholder interviews. It will discuss these findings in the context of the existing literature, emphasizing their significance and the contributions this research has made.

It will also discuss the study's limitations, their potential impact on the results, and potential ways to mitigate these limitations in future research. It will discuss the practical and academic implications of the research, demonstrating how the findings can guide policy and industry practices, and stimulate further academic research.

It will integrate the findings into the broader literature and discuss the limitations of the study in relation to how this thesis contributes to the field of circular innovation and sustainable energy practices, more specifically within the Indian solar industry, which is rapidly expanding.

5.1. Key Findings

The research in this thesis aimed to identify the critical drivers and barriers to circular innovation in the Indian photovoltaic sector, with a focus on the end-of-life management of photovoltaic panels. This section revisits the major findings in relation to these drivers and barriers, contextualizes them with the broader literature on the issue, and reflects on the implications for the future of circular innovation in India's solar industry. These chosen barriers, drivers, and strategies will provide a fair representation of practical problems from the industry and theoretical input one's research can make. This will ensure that the discussion is based on real problems but also contributes to the academic debate on circular innovation.

All possible barriers, drivers, and strategies would overwhelm the discussion and reduce its focus. This approach assists in narrowing down the focus to only the most pertinent factors, thereby maintaining a razor-sharp and focused argument that is highly relevant to the research questions. This, in turn, enhances the narrative flow and effectively communicates the key messages from the research. We specifically selected the barriers, drivers, and strategies discussed due to their unique relevance to the Indian context. The PV sector in India is rapidly growing, but it also faces challenges unique to that country in terms of infrastructure, regulation, and market dynamics. These factors highlight context-specific challenges and opportunities, making the discussion more relevant and impactful for stakeholders in India.

5.1.1. Drivers of Circular Innovation

Some drivers emerged that would prove very instrumental in the process of circular innovation in the Indian PV sector: economic incentives, enabling government policies, technology advancement, and collaborative networks. Out of all possible drivers, the following four represent the most influential factors that would promote circular innovation in the Indian PV sector: economic incentives, favourable government policies, technological advancement, and collaborative networks. The research findings and existing literature help to facilitate these drivers, which are critical for implementing circular economy practices.

The identification of economic incentives, which guarantee cost reduction and resource efficiency through circular practices, was one of the primary drivers. Recycling and remanufacturing have the potential to significantly reduce production costs, particularly in price-sensitive markets like India. This finding aligns with literature review describing the economic viability of circular practices in relation to decreasing operational costs and improving competitiveness.

The conducive government policies are an equally important factor. In India, the regulatory framework, which includes a wide range of policies related to renewable energy and waste management, has facilitated the adoption of circular practices. However, the effectiveness of these policies hinges on their consistent implementation and the availability of clear guidelines for industry compliance, as the stakeholder interviews highlighted. The findings align with the literature review, asserting that the policy framework, while crucial, becomes ineffective without effective enforcement and industry collaboration.

The other major drivers were technological advancements in recycling and waste management technologies. This sector can adopt circular practices significantly by enhancing the overall efficiency and cost-effectiveness of the PV panel recycling process. Collaborative networks were an important enabler of circular innovation. This research identified the creation of partnerships among industry stakeholders in manufacturing, recycling, and government agencies as a key factor in overcoming the challenges associated with EOL management of PV panels. This finding is concurrent with the literature review, which laid emphasis on consolidated efforts to achieve sustainability in the PV sector.

5.1.2. Barriers to Circular Innovation

The research identified a number of important barriers that significantly hinder the dissemination of circular practices in the Indian photovoltaic sector, despite the presence of strong drivers. There is no doubt that the main obstacles—among them, high recycling costs, limited infrastructure, complex regulatory environment, and lack of awareness—observed in the research raise questions about the feasibility and scalability of circular innovation strategies in the Indian case. It would therefore pinpoint, in highlighting these barriers, the most important issues that must be overcome in the pursuit of circular innovation.

High recycling costs ranked as one of the critical barriers. Especially so in a developing economy such as India, the cost of investment to set up a recycling facility and its operations is pretty high. The existing market's lack of economies of scale further exacerbates this, making it challenging for firms to justify the necessary recycling investments. These findings replicate the findings of the literature review, which found high costs to be one of the critical barriers to Circular Economy principles in emerging markets.

Another important barrier is the limited infrastructure for waste management and recycling. The existing infrastructure in India is incapable of addressing the rising inflows of PV waste, resulting in inefficiency and increased operational costs. This barrier overlaps with the findings of literature review, which suggests that unsatisfactory infrastructure acts as a major bottleneck in the transition to the circular economy in most developing countries.

Also available is the complex regulatory environment, where stakeholders have indicated challenges due to the inconsistencies and sometimes conflicting nature of regulations. This can create uncertainty for businesses looking to invest in circular practices. Indeed, this same complexity of the regulatory environment is also noted in the literature review, which suggests that streamlined and clear regulations are of essence in fostering circular innovation.

The most important barrier that emerged was a lack of awareness among consumers and businesses about the benefits associated with circular practices. Given the general resistance to change among stakeholders, a low level of awareness and understanding of long-term benefits will hinder the adoption of circular practices. In the literature review we found that the successful implementation of the circular economy initiative, identified awareness as a key factor.

5.2. Integration with Literature

The section presents the findings of this research in a broader context of academic discourse on circular innovation, the photovoltaic sector, and sustainable energy practices. By comparing and contrasting the drivers, barriers, and strategies identified in this study with existing literature, we can better understand how the research has contributed to and expanded knowledge in these fields.

5.2.1. Alignment with Existing Research

Essentially, the thesis findings confirm existing literature on circular innovation and the PV sector, particularly in India's emerging markets. It identifies drivers of circular innovation—economic incentives, technological advancement, and enabling government policies—which are very similar to the broader literature. For example, literature review stress the economic benefits of circular practices in terms of cost reduction and improvement in resource efficiency, findings that align with the economic incentives identified in this thesis. In the literature review we have found extensively documented the role of technological innovation as a catalyst for circular innovation, emphasizing how innovation in recycling technologies enables the emergence of sustainable practices in the PV sector.

Moreover, the impact of supportive government policies as a driver is also in line with the literature review, which put forward that supportive regulatory frameworks are the real drivers for the adoption of circular practices. However, this thesis contributes to the debate by emphasizing the importance of having not only an existing policy but also proper guidelines for its implementation in a country like India, where policy implementation can sometimes be uneven. Another area in which this study aligns with the literature is collaborative networks as a driver of circular innovation. The literature states that stakeholder collaboration is a trigger factor for sustainable innovation, and this thesis takes this view. The focus on networks emphasizes the need for collective action when trying to overcome the complex challenges associated with circular innovation in the PV sector.

5.2.2. Divergence from Existing Research

While there is a lot of agreement with existing literature, this paper also points out some findings that do diverge or extend existing knowledge in certain regards, and most importantly, barriers to circular innovation. A significant divergence from the literature is the finding that high recycling costs are an important barrier in the Indian PV sector. While the literature review acknowledges the financial challenges of circularity, this thesis offers a more precise appreciation because it links such costs with the lack of economies of scale in the Indian PV market. This link suggests that while high costs are a recognised barrier globally, their impact in emerging markets could be felt more keenly because of market size and infrastructure limitations.

The complex regulatory environment identified in this study also adds a layer of complexity not fully explored in existing literature. The literature review provides a more comprehensive discussion of regulatory challenges, whereas this research provides specific examples of how inconsistencies and sometimes conflicting regulations in India pose significant obstacles for business enterprises seeking to implement circular practices. This suggests that, in addition to policy clarity, coherence, and alignment, regulations that span various governmental levels and sectors are also bilingual. This research confirms the ongoing findings by focusing on the ”lack of awareness” barrier. While the literature review postulate that an awareness process precedes any circular action, this research has found in-depth persistent resistance to change due to a lack of understanding of long-term benefits. This implies that an awareness campaign in itself would not be enough, and a more comprehensive approach that involves education, incentives, and demonstration projects may well prove necessary in changing mindsets and behaviours.

5.2.3. Contribution to Theoretical Frameworks

Probably one of the most important theoretical contributions of this thesis is the adaptation of the TIS framework to the Indian PV sector. Even though in many studies on technological innovation, the use of the TIS framework is not new, it is applied in the context of an emerging market and particularly within the PV industry, which allows more tailored analysis with regard to the unique drivers and barriers of the Indian context.

This thesis not only identifies barriers but also offers practical solutions in form of niche strategies to enhance the usefulness of the TIS framework for policymakers and industry stakeholders. Furthermore, the emphasis on reverse logistics as one of the most important building block within the TIS framework contributes to the recent call for more holistic frameworks in product life cycles from cradle to grave. This thesis contributes to the slowly emerging discourse by pointing out how such elements are particularly relevant in the case of circular innovation, for which managing material and information flows forms a precondition of success.

5.3. Limitations of the Study

Despite providing valuable insights into the drivers and barriers of circular innovation in the Indian PV sector, this research has several limitations that require attention. These limitations probably biased the findings and therefore should be borne in mind when interpreting the results with their implications.

5.3.1. Scope of the Study

One of the key limitations of this study was its scope, which was purposefully restricted to the Indian PV sector, particularly for the end-of-life management of photovoltaic panels. While this allowed us to go into great detail about certain specific challenges and opportunities within the

Indian context, it has limited the generalizability of the findings to other regions or sectors. The drivers and barriers identified in this study may not apply fully to other countries with different regulatory, economic, or technological environments. Furthermore, these niche strategies are explored according to the Indian market; hence, how far their adoption will be effective in other contexts will need further study.

5.3.2. Data Collection and Sampling

The limited number of interviews used to sample stakeholders presents another limitation in the data collection process. While the interviews provided very rich qualitative insights, the number of samples was relatively small, and the main occupations represented by participants were those in the industry and policy-making sectors. This may have inscribed a quite narrow view of the problems, not considering views from other key stakeholders, such as informal market and ministry of new and renewable energy operating in areas of the PV value chain. Furthermore, the subjective nature of qualitative data means that interviewees' personal biases or experiences could shape the findings.

5.3.3. Potential Biases

It is necessary to declare any potential biases in the research process. The researcher's personal views and decision-making may have influenced the selection of reviewed literature, the formulation of research questions, and the interpretation of data. While great care was exercised in maintaining objectivity and rigour throughout the research process, it shall also be acknowledged that the study is not completely free from personal assumptions and context.

5.3.4. TIS Framework Application

While applying the TIS framework provides a structured approach to the analysis of circular innovation, there are also some limitations. In this research, we applied the framework, originally developed for the analysis of technological innovations systems, to specifically focus on circular innovation within the PV sector. While this application was relevant and useful, it might have lost some nuances, especially those associated with the broader socio-economic and cultural conditions that impact circular practices. Anyway, it only looks at the TIS framework as a whole, so it might miss some of the smaller-scale dynamics that are also important to circular innovations, like how individual businesses act or how people in the same community interact with each other.

The use of the TIS framework for the analysis of circular innovation in India's photovoltaic recycling sector has several limitations. This framework was designed for the introduction of high-tech products in Europe, which may not fully align with the socio-economic context and unique regulatory setting of India, not to mention the regulatory environment that is still under construction. Moreover, the framework might not adequately tackle the variety of materials utilized in photovoltaic panels, the varying quality of these materials, and the related logistics of collection and processing. The other critical limitation of the application of the framework for my case is its inability to integrate the informal sector in PV recycling in India, which occurs outside formal regulatory and economic systems, resulting in problems related to the assurance of quality and working practices. In light of the rapidly evolving recycling technology and related environmental laws, the framework requires increased dynamism and adequate flexibility to adapt to ongoing changes.

5.4. Implications

5.4.1. Practical Implications

The circularity research results in photovoltaic recycling in India entail major practical implications for key stakeholders: policymakers, industry players, and researchers. Indeed, these steps and strategic insights would overcome the barriers perceived to attain a much more sustainable circular economy in the PV sector.

For Policy Development and Implementation

These results strongly emphasize an urgent need for comprehensive and legally binding regulations to support PV recycling in India. Policymakers are called upon to put in place well-defined, coherent, and stringent regulations that give an impetus to solar panel recycling by making it easier to undertake while encouraging the development of circular innovation. Efficient implementation of extended producer responsibility will ensure manufacturers are held fully responsible for end-of-life management of their products. In addition to subsidies, tax breaks, and other financial incentives, this will reduce the exorbitantly high upfront cost of setting up recycling facilities to attract more private sector investments.

The results demonstrate that there is at least a case for ongoing support from regulators in terms of removing some of the barriers to entry, such as high recycling costs and limited infrastructure. Indeed, policymakers can do a lot to diffuse the practice of sustainability within the PV industry by designing appropriate policies aimed at smoothing the recycling process and offering economic incentives. Pilot and demonstration projects will embody practical testing areas for scalable recycling initiatives and provide concrete examples that inform broader policy decisions.

For Industry Stakeholders

The results highlight the need for producers and recyclers to invest in circular innovations, prompting the question of what makes both business and environmental sense. Integration of new advanced recycling techniques into current production methods can vastly improve the quality of reclaimed products and the profits accrued in the recycling process. The study suggests practical strategies for implementing recycling facilities and introduces leasing models for PV panels, providing clear pathways for business organisations to integrate circular practices. These strategies not only lower the environmental impact but also bring down costs and improve resource efficiency.

The research underlines the importance of cooperation and engagement with stakeholders. Industry players must, therefore, enter into collaborative relationships with actors engaged in recycling and logistics with a view to devising effective systems to recycle and sort out-of-use solar modules, establishing reverse logistics, and reducing the overall cost. Companies can actively participate in the circular economy by prioritizing these collaborative networks, rethinking their business models, and focusing on life-cycle product management, particularly end-of-life management.

For the Informal Sector

While the informal sector has undoubtedly been one of India's main drivers of the recycling ecosystem, proper integration into official recycling systems will enhance overall efficiency and quality. Training programs and certification schemes will help such informal recyclers adopt safer and more effective recycling practices. Formal recognition and participation will improve working conditions and provide economic benefits to a large workforce engaged in recycling activities.

5.4.2. Academic Implications

It is highly relevant to India's photovoltaic recycling industry, and there are also several long-term academic implications that open up a number of options for further research and theoretical development. These varied implications cut across a wide range of disciplines: theoretical frameworks, circular economy research and interdisciplinary opportunities.

Contribution to Theoretical Frameworks

Theoretical framework contribution can be expected, specifically in the area of circular innovation, through the adoption or application of the TIS framework. This thesis will contribute to the extended application of this framework within the context of the Indian PV sector and further showcase its utility when applied to the analysis of circular economy practices within emerging markets. The niche strategies in the TIS framework also provides a novel approach to address specific barriers to innovation. It may serve as a basis for future research that aims to explore circular innovation in other sectors or regions using the adapted TIS framework as a guideline.

Advancement of Circular Economy Research

This research thus offers important contributions to the theoretical debate on practices in the circular economy, particularly in the renewable energy sector of emerging markets. The findings of this study offer valuable insights into the exact identification of financial barriers and economic feasibility of PV recycling, which can also feed into economic models and cost-benefit analyses on recycling facility investments. Furthermore, the careful consideration given to the regulatory framework, as well as a step towards ambitious recycling regulation and financial incentives, provide a foundation for developing policy recommendations in support of circular economies in emerging economies. The literature, which previously largely consisted of studies from developed nations, has benefited from this emphasis on the Indian PV sector. This shift emphasizes that there are some unique challenges and opportunities that emerging markets face, necessitating further exploration and refinement of theoretical models of circular innovation applicable to such regions.

Interdisciplinary Research Opportunities

The interdisciplinary nature of this research opens new avenues for cooperation in the areas of engineering, environmental science, economics, and policy analysis. Further research in the subject area could benefit from exploring the intersections between these fields. This could include, for example, understanding the economic impact of circular innovation strategies on the wider Indian economy or assessing the potential environmental savings that such circular practices would bring to the PV sector through sophisticated lifecycle assessment tools. Therefore, the research has implications for interdisciplinary approaches to meeting complex global challenges such as sustainable development and resource management.

5.5. Suggestions for Future Study

This research has highlighted some of the drivers, barriers, and strategies for circular innovation in the Indian PV sector. However, several areas are open to further research. The recommendations given below for future research are primarily aimed at remediating limitations identified in this study, making possible extensions to the scope of research, and deepening the understanding gained regarding circular innovation in the photovoltaic industry and beyond.

5.5.1. Expanding the Geographic Scope

The current study primarily focused on the Indian context. This context presents numerous challenges and opportunities for circular innovation. Future studies could expand their geographical scope to compare India with other emerging markets or even developing or undeveloped countries. Researchers may conduct another study to examine the impact of various regulatory environments and cultural factors on the adoption of circular practices in the PV sector. In that respect, comparative analyses might allow for the adoption of best practices identification across different regions, which would provide a more global understanding of circular innovation.

5.5.2. Longitudinal Studies on Circular Innovation

Due to the limited timespan of this research, one clear avenue for future research is through longitudinal studies examining the diffusion of circular innovation strategies and their influence over time. In this respect, long-term studies on the effectiveness of proposed niche strategies and how drivers and barriers change as the photovoltaic market further matures would be very useful. Longitudinal research may also recognize the impact of emerging trends, such as rapid technological changes and changes in policies, on the PV industry's sustainability. Might also help in the integration of informal market.

5.5.3. Quantitative Analysis and Broader Stakeholder Engagement

While the current study was based essentially on qualitative data, with interviews conducted only among a small number of stakeholders, further research should incorporate deeper quantitative analysis. Surveys covering larger and more representative samples of relevant stakeholders, such as consumers, small businesses, and local communities, could then achieve more general implications for perceptions and behaviours concerning circular innovation. We can also apply econometric modelling to quantify the potential impacts of circular strategies on the PV sector and the overall economy. Another critical area of future research would be the involvement of the informal sector in PV recycling in India. Since almost all activities related to recycling take place in the informal sector, understanding the dynamics, capacities, and problems of the informal sector would be quite important. Future research should indicate how the informal sector could be integrated into the official recycling framework with regard to quality standards, working practices, and environmental performance so that there may be increased effectiveness and sustainability of the system.

5.5.4. Policy and Regulatory Framework Analysis

However, building on the findings that identified the complex regulatory environment as one of the key barriers to circular innovation, further research should focus on a detailed investigation of policy and regulatory frameworks. Researchers could conduct investigations to determine the impact of various policy instruments, including subsidies, tax incentives, and regulations, on the adoption of circular practices. For instance, it would delve deeper into the design and implementation of policies that support circular innovation, ensuring they are coherent and aligned across various sectors and levels of government. This, in turn, will guide policymakers on how to create an enabling environment for sustainable practices.

6 Conclusions

This thesis examined how niche strategies can initiate, geographically anchor, and guide circular innovation of end-of-life photovoltaic panels in India. Through its findings, this research provides insights into the drivers and barriers to circular innovation for EOL PV panels in India. By identifying suitable niche strategies by applying the TIS framework and adapting the TIS framework to the research case, this study brought up a comprehensive strategy for promoting circularity in the PV sector. If effectively implemented, these strategies can help overcome the existing challenges in achieving circular innovation of PV waste in India, hence contributing to the country's environmental sustainability and economic growth objectives. Future research should focus on further refining these strategies and exploring their practical implementation in real-world scenarios.

6.1. Research Questions

The main research question guiding this research was: "What are the key drivers and barriers to circular innovation for EOL PV panels in India, and how can the application of niche strategies help overcome these challenges?"

To answer this question, several sub-questions were addressed:

1. What are the drivers to circularity of PV in India?
2. What are the barriers to circularity of PV in India?
3. Which niche strategies would be best suited for circularity of PV in India?
4. How to adapt the framework for the case of circular innovation in India?

6.1.1. How were the Research Questions Answered

The main research question was answered by identifying the key drivers and barriers to circular innovation in the context of EOL PV panels in India, and then proposing suitable niche strategies to address these challenges. The Technological Innovation System (TIS) framework was applied and adapted to this context. Insights from literature reviews, interviews with industry professionals, and case studies were used to propose niche strategies.

How were the Sub-questions Answered

1. What are the drivers to circularity of PV in India?

A number of critical factors have an impact on India's drive for PV panel recycling. These drivers underscore the necessity for recycling practices and highlight the multifaceted benefits such initiatives can bring to the Indian solar industry. Here are the key drivers for PV panel recycling in India:

Increasing Energy Demands India's rapid population growth, urbanisation, and modernisation are significantly boosting energy demand across the nation. As the country strives to meet these escalating energy needs, sustainable solutions become imperative. Solar PV systems emerge as a highly reliable and environmentally friendly energy source, essential for addressing the increasing demand. The sustainable energy goals push for a comprehensive approach to energy generation, where recycling PV panels can play a vital role in maintaining the efficiency and sustainability of solar power systems.

Augmentation of Solar Capacity India's ambitious solar energy target highlights the dramatic increase in solar power installations. The large-scale deployment of solar panels is integral to India's energy strategy. This expansion necessitates efficient end-of-life management of solar panels to sustain the solar infrastructure's lifecycle and functionality. Recycling can significantly contribute to this goal by ensuring that old and damaged panels are effectively managed, reducing waste, and promoting the reuse of materials.

Premature PV Waste Generation The generation of PV waste before panels reach their end of life due to damage during transportation, installation, operation, or natural calamities like floods and earthquakes presents a significant challenge. This situation emphasises the need for systems to manage and mitigate waste effectively. Efficient recycling processes can effectively handle premature waste, guaranteeing the proper recycling of even damaged panels, thereby reducing overall waste and conserving resources.

High Dependence on Imports India's high dependence on imports for the production and installation of solar PVs creates a strategic vulnerability. Developing a circular economy for PV panels through recycling can reduce reliance on imported materials. By enhancing the recycling and reuse practices of existing solar panels, India can secure a steady supply of necessary materials, thereby minimising dependency on external sources and stabilising the supply chain.

Availability and Affordability of Materials The availability and affordability of materials required for the manufacture of solar PV systems are critical for the feasibility of circular practices. Efficient recycling ensures a steady supply of these materials, reducing the need for virgin resources. This not only makes the production of new panels more sustainable but also economically viable by lowering the cost of materials through the reuse of recycled components.

Projected EOL PV Waste India is expected to produce 2.95 billion metric tonnes of end-of-life (EOL) solar PV waste, including PVs and balance of system (BOS) components, between 2020 and 2047. This projection highlights the urgent need for sustainable waste management strategies. Recycling presents a viable solution to manage this enormous volume of waste, mitigating environmental impact and promoting the sustainable disposal of PV panels.

Hazardous Materials in PV Waste The presence of hazardous materials like lead, lithium, tin, and cadmium in PV waste poses significant environmental risks. Unscientific disposal of these materials can lead to soil and water pollution, necessitating effective recycling and disposal methods. Robust recycling processes guarantee the safe extraction and management of hazardous components, thereby safeguarding environmental health.

Critical Metals Supply Crunch The competitive consumption and supply crunch of critical metals such as silicon, germanium, and lithium used in manufacturing solar panels underline the importance of recycling. Ensuring the recovery and reuse of these metals can mitigate supply chain risks. Recycling can secure a supply of critical metals needed for manufacturing new panels, reducing the pressure on mining and importing raw materials.

Regulatory Gaps Currently, in India's waste management guidelines, there is no specific definition of solar PV waste. It is treated as general e-waste under the Ministry of Environment, Forestry, and Climate Change (MoEF&CC). For effective management, clear regulations tailored to PV waste are essential. The development of specific policies and guidelines can provide a framework for proper recycling practices, ensuring compliance and promoting sustainable waste management.

Need for Regulations and Incentives Appropriate regulations and incentives are required to transition solar PV waste management from a linear to a circular economy. Government regulations can mandate sustainable practices, while incentives can support the development of robust recycling infrastructure. Financial incentives and supportive policies can encourage businesses and consumers to participate actively in recycling programs, fostering a culture of sustainability.

2. What are the barriers to circularity of PV in India?
On the path towards achieving circularity in the photovoltaic sector in India, there are a number of challenges to effectively recycling and reusing solar panels in India. These barriers underlie the country's technological, economic, regulatory, and socio-cultural framework, presenting an extremely complex landscape that would necessitate multifaceted solutions. It's hard to make progress towards a sustainable circular economy because of the complicated technology, high costs, lack of dedicated facilities, ineffective regulatory frameworks, lack of leadership by multilevel governments, sociocultural challenges, and inefficient logistics. These barriers require a collective responsibility of the government, industry, and consumers to map and enforce comprehensive context-specific strategies that can promote PV material recycling and reuse in India.

Technological Barriers

Recycling May Cause Degradation of the Quality of Recovered Silicon The complex process of recycling PV panels often leads to the degradation of silicon quality, making the recycled material less efficient for future use.

Lack of Formal Recycling Facilities India lacks formal recycling facilities that are equipped to handle the specific needs of PV panel recycling, such as detaching glass and aluminum from the modules.

Absence of Structured Collection and Sorting Facilities There is no formal logistical route for the collection and sorting of end-of-life (EoL) panels, leading to inefficiencies and missed opportunities for material recovery.

Economic Barriers

High Initial Setup and Reverse Logistics Costs The establishment of recycling facilities and efficient logistics for collecting and processing PV panels involves high initial costs, which are a significant economic barrier.

Economic Viability of Recycling Certain Materials The financial return from recycling specific materials like copper and silver is uncertain and complex, making the economic viability of such processes questionable.

Lack of Economic Incentives There is a lack of economic incentives for recyclers and manufacturers to enter the business of EoL management of solar PV waste.

Lack of Subsidies and Incentives Without government subsidies and financial incentives, the high costs of setting up and operating recycling facilities can deter companies from investing in this sector.

Promotion of R&D Initiatives Limited promotion of research and development initiatives in relation to EoL management of solar PV waste affects the evaluation and development of new and effective recycling technologies.

Regulatory Barriers

Absence of Definition and Specific Regulations The absence of a clear definition of solar PV waste and specific regulations for its disposal and recycling complicates the management of PV waste under the Ministry of Environment, Forest, and Climate Change (MoEF&CC) guidelines.

Lack of Policy Regulations The lack of policy regulations to streamline the collection, recovery, and recycling of solar PV waste creates a significant barrier.

Ineffective Implementation of Extended Producer Responsibility (EPR) Although an EPR scheme exists, its ineffective implementation due to weak enforcement mechanisms hinders its potential to solve reverse logistics issues.

Lack of Concrete Structure to Policies and Clarity on How to Implement Them There is a significant ambiguity in the policy structure and implementation guidelines, which complicates the effective application of recycling policies.

Lack of Government Leadership and Initiatives The absence of proactive government leadership and initiatives to drive policy development and provide financial incentives is a critical barrier.

Need for Specialized Institutions and Norms for PV Panel Recycling The lack of specialized institutions and clear norms for PV panel recycling hinders the establishment of effective recycling practices.

Appropriate Regulations and Incentives There is a need for regulations and incentives tailored to facilitate the transition of solar PV management from a linear to a circular economy.

MNRE Blueprint The Ministry of New and Renewable Energy (MNRE) issued a blueprint for the disposal and recycling of PV equipment in 2019, but its on-ground implementation remains lacking.

Socio-Cultural Barriers

Lack of Consumer Awareness A significant barrier is the lack of consumer awareness and participation in the EoL management of solar PV waste, which affects the effectiveness of recycling initiatives.

Lack of Accountability There is a lack of accountability within the industry for managing solar PV waste at the EoL stage, which hampers coordinated efforts for effective recycling.

Lack of Coordination Effective recycling requires coordination among various stakeholders, including ministries, industry stakeholders, and recyclers. The current lack of coordination is a significant barrier.

Non-inclusion of BOS (Balance of System) The non-inclusion of BOS components like inverters and batteries under the e-waste management rules further complicates the comprehensive management of solar PV waste.

3. Which niche strategies would be best suited for the circularity of PV in India?
To overcome these barriers, several niche strategies are well-suited for promoting circularity in the PV sector in India:

- **Demo, Experiment, and Develop Strategy:** This strategy focuses on controlled demonstrations and experiments to develop advanced recycling technologies. Creating pilot projects that test and refine methods for recycling silicon without significant degradation can improve material recovery efficiency and quality. Research institutions and industry leaders collaborate to ensure the technology meets practical needs and standards, just as they test new semiconductor technologies in controlled environments before mass production.
- **Redesign Niche Strategy:** Redesigning the recycling process to be more cost-effective can boost economic viability. This strategy focuses on simplifying the product or process to reduce costs and resources needed. It helps adapt the technology to better meet market demands and improve economic feasibility.
- **Subsidized Niche Strategy:** It is important to provide financial subsidies to offset some of the high costs required to develop recycling facilities and logistics. Government incentives can reduce some of the financial impediments that would prevent companies from considering a shift in investment towards developing the infrastructure for recycling. In other areas, this has worked. For instance, the official subsidies implied by support for renewable energy have drastically increased its adoption rate.
- **Top Niche Strategy:** Targeting high-value market segments that are willing to pay a premium amount for recycled materials can improve the economic viability of recycling

operations. For instance, the supply of high-quality recycled material, essential for electronics and larger high-tech semiconductor and processing equipment manufacturing, can significantly boost the profitability of PV panel recycling.

- **Hybridization or Adaptor Strategy:** Adapting existing e-waste facilities to handle PV waste is an economical solution. Upgrading such facilities with new technologies can thus build on already existing infrastructure to create specialized PV panel recycling capabilities, which would minimize initial investment costs and allow the quick establishment of effective recycling systems.

  This would enable the already existing logistics infrastructure to be harnessed and ready for processing the recycling of PV panels, increasing efficiency. In the case of further integration of reverse logistics into the current supply chains and collaboration with logistics companies, collection and sorting processes could get smoothed out to bring down the costs and improve the recovery rate of materials.

  Utilizing existing infrastructure and integrating new recycling processes with current systems can improve EPR implementation. This strategy helps in ensuring that complementary products and services work well together, facilitating a smoother recycling process.

- **Dedicated System or Standalone Niche Strategy:** Developing specialised recycling facilities can address this barrier. This strategy focuses on creating independent systems dedicated to recycling PV waste, ensuring proper handling and processing.

  Developing dedicated institutions and frameworks for PV panel recycling can effectively address the gap and support the industry. Similar to how specialised research institutes for renewable energy have driven technological advancements in that field, dedicated PV recycling institutions can drive innovation and standardisation.

- **Educate:** It is important to increase awareness and understand the Extended Producer Responsibility (EPR) among manufacturers and consumers. Campaigns can target the incentives that come with implementing EPR, which range from reducing environmental impact to potentially saving costs when recycling products. Campaigns involve workshops, seminars, and cooperation with industry associations aimed at spreading best practice and encouraging compliance with EPR principles.

- **Hybridization or Adaptor Niche Strategy:** Utilizing existing infrastructure and integrating new recycling processes with current systems can improve EPR implementation. This strategy helps in ensuring that complementary products and services work well together, facilitating a smoother recycling process.

- **Geographic Niche Strategy:** Pilot programs in states and localities with more conducive policies and infrastructure can act as examples for broader applications. These areas are better positioned to demonstrate the feasibility and benefits that come with effective recycling practices, leading to increased adoption throughout the country.

- **Networking and Lobbying Strategy:** Building alliances among stakeholders, including industry, government, and NGOs, to advocate for clear and supportive policies is critical. Strategic lobbying efforts can push for regulatory changes that provide clarity and support for recycling initiatives, similar to successful lobbying efforts in the renewable energy sector.

- **Lead User Niche Strategy:** Engaging innovators and lead users can provide valuable feedback and co-develop solutions for policy implementation. This strategy encourages collaboration and helps in forming a clear and effective structure for recycling policies.

4. How to adapt the framework for the case of circular innovation in India?
Adapting the Technology Innovation System (TIS) framework to analyse circular innovation in the photovoltaic (PV) recycling sector in India required an innovative and integrative approach. The process began by critically examining the existing TIS framework and recognising that, while it provides a foundation for analysing technological innovation, it needed modification to address the unique challenges and opportunities presented by India's socio-economic, regulatory, and technological environment.

The first step in this adaptation involved conducting a comprehensive review of the literature on PV recycling, specifically within the Indian context. This review highlighted critical aspects of India's market dynamics, regulatory environment, technological capabilities, and socio-cultural factors that influence the circular innovation process. It became evident that existing frameworks, including those developed by Raghav and Jules for circular innovation, each addressed different facets of the circular economy but did not encapsulate the complex landscape of India's PV recycling sector.

Recognising this, the the task of integrating the insights from Raghav and Jules' frameworks into a cohesive adaptation of the TIS framework was conducted. This combined framework served as a starting point, which was then further refined to address the specific conditions identified through the literature review. The integration process allowed for the creation of a more holistic and context-sensitive version of the TIS framework.

To validate and further refine this adapted framework for the research case, in-depth interviews with industry stakeholders were conducted. These interviews were crucial in confirming the relevance of the barriers and drivers identified from the literature and in gaining practical insights that the literature alone could not provide. Stakeholders offered perspectives on the challenges of implementing circular innovation in India, such as the economic and logistical difficulties in establishing dedicated recycling facilities and the dominance of the informal sector in recycling activities. These insights were instrumental in refining the indicators and modifying the framework to better reflect the realities of the Indian context.

The final adapted TIS framework incorporated these refined indicators, ensuring that it accurately reflected the unique economic, regulatory, and technological conditions in India. The result was a robust analytical tool capable of addressing the specific challenges and opportunities identified throughout the research process. This framework is not merely a direct application of the original TIS model but a carefully adapted version that considers the specific needs of the Indian PV recycling sector.

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