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Structural Mismatch: the EU WEEE Directive and Photovoltaic End-of-Life Management

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Abstract

Photovoltaic (PV) technology stands at the core of the EU's energy transition, yet its rapid expansion points to an inevitable surge in future waste streams. Currently, decommissioned modules are managed under the Waste Electrical and Electronic Equipment (WEEE) Directive. This framework was originally tailored for short-lived consumer electronics, creating a profound structural mismatch with PV modules, which function as durable and high-value power generation equipment. Through a mixed-methods approach, this thesis integrates quantitative market data from France, Germany and Sweden with qualitative expert interviews to assess this mismatch. Three main misalignments are identified. Financially, the pay-as-you-go mechanism is not suitable for products with a 30-year lifespan, which risks funding deficits and the accumulation of orphan waste. Logistically, municipal collection networks are inadequate for heavy and fragile panels, leading to high costs and physical damage. Regarding value recovery, weight-based compliance targets incentivize downcycling and undermine reuse potential and the retrieval of valuable and strategic materials such as silver and high-purity silicon. Patching the existing framework is no longer sufficient to meet the challenges ahead. This thesis recommends separating PV modules from the WEEE framework and setting a dedicated legislation for this product group. By adopting measures including Digital Product Passports (DPPs), independent trust funds and material-specific recovery targets, the EU can drive PV End-of-Life (EoL) toward a closed-loop system of value retention.

Keywords: Photovoltaic; End-of-Life; WEEE Directive; structural mismatch; extended producer responsibility; value retention

Executive Summary

Background and Aims

As the EU accelerates its energy transition, photovoltaic (PV) technology has moved to the center of its strategic infrastructure. This rapid deployment, however, is generating an inevitable downstream surge in end-of-life (EoL) waste. Retired PV modules are currently managed under the Waste Electrical and Electronic Equipment (WEEE) Directive, a framework originally designed for short-lived consumer electronics. When applied to PV modules, which are durable, high-value power generation equipment with an operational lifespan of 25 to 30 years, this regulatory framework creates a profound structural mismatch.

This thesis systematically evaluates the structural incompatibility between the WEEE framework and the physical and operational characteristics of PV modules as long-term energy infrastructure. By examining how this mismatch disrupts financial, logistical and value-recovery operations, the study identifies major problems in current practice. Building on these findings, the thesis proposes a policy roadmap to transition PV EoL management from a reactive waste burden to a circular system capable of retaining material, economic and strategic value throughout the product lifecycle. To fulfill this aim, the following research questions are studied:

1. What misalignments exist between the WEEE Directive and the operational realities of PV EoL management?

2. How do these misalignments affect logistical efficiency, long-term financial viability and strategic value recovery?

3. What policy interventions can best shift PV EoL management from a passive waste-disposal model to a proactive value retention system?

Methodology

This research employs a sequential explanatory mixed-methods design. By integrating quantitative analysis with qualitative interviews, the thesis uses France, Germany, and Sweden as examples. These three nations represent distinct implementation pathways of the WEEE Directive. France operates under a centralized monopoly through Soren. Germany utilizes a decentralized, competitive market model overseen by Stiftung EAR. Sweden relies on a semi-centralized system integrated with municipal networks. Examining these varied approaches ensures the findings transcend national administrative anomalies and highlight systemic, EU-wide challenges.

Regarding theory, this thesis constructs a three-dimensional lifecycle governance framework. It maps several core concepts onto the entire lifecycle of PV modules, specifically upstream design and manufacturing, midstream market placement and operations and downstream end-of-life processing. These concepts include circular economy principles, PV-specific R-strategies, Design for Environment (DfE), institutional path dependency, and value retention theory. This integrated conceptual framework serves as a vital analytical lens. It explains why the WEEE Directive is not the best fit when applied to durable energy generation equipment.

The quantitative phase relies primarily on the annual operational reports of the respective Producer Responsibility Organizations (PROs). This core dataset is supplemented by policy and market analyses from institutions such as IEA PVPS, JRC, and SolarPower Europe. Relevant techno-economic parameters from academic literature are also incorporated. The thesis

conducts cross-market comparisons and baseline estimations on key indicators, including collection rates, eco-contribution fees, logistical costs, and material recovery performance. This process provides evidence of the misalignments and quantifies their impact.

Following this, the qualitative phase utilizes semi-structured interviews with eight senior experts spanning policy researchers, PROs, recyclers and industry practitioners. These discussions bridge the data gaps of the quantitative phase, explore the complex stakeholder dynamics and practical operational realities that numbers alone cannot capture.

Main Findings

This thesis confirms that regardless of specific national transpositions, the systemics flaws of the WEEE framework consistently emerge in PV EoL operations. This structural mismatch manifests in three dimensions:

A fundamental financial mismatch exists between the WEEE Directive's pay-as-you-go mechanism and the long lifecycle of PV modules. Current upfront fee collections are inadequate compared to projected EoL treatment costs. By ignoring inflation and price increases over a three-decade period, this system guarantees a severe future funding shortfall. In parallel, strict financial guarantee mandates companies to freeze significant capital or purchase expensive insurance, which severely drains their operational liquidity. Even more alarming is the combination of loose B2B regulations, widespread free-riding by cross-border e-commerce platforms and the constant threat of corporate bankruptcy. Together, these factors may trigger a surge of orphan waste, unfairly transferring the ultimate cleanup costs to future taxpayers and compliant enterprises.

Logistically, existing municipal e-waste collection networks cannot accommodate the physical realities of PV modules. These panels are bulky, heavy, and fragile. Their installations are also highly dispersed, particularly in low-density countries like Sweden. Furthermore, dismantling involves high-voltage electrical hazards that demand specialized equipment and certified personnel. However, current PRO funding pools typically exclude these on-site removal costs, bottlenecking collection at the source. During long-distance transport, rough handling and improper stacking cause widespread glass breakage. This physical damage eliminates any potential for module reuse. More critically, shattered glass contaminates the internal silicon wafers and silver grid lines, permanently destroying the baseline conditions required for high-value material recovery.

Regarding value recovery, the weight-based targets of the WEEE Directive generate perverse incentives. Glass and aluminum frames constitute the vast majority of a module's weight. Consequently, recyclers can easily achieve compliance through simple mechanical shredding to extract these bulk fractions. This negates any commercial rationale to invest in expensive technologies capable of recovering trace amounts of silver and high-purity silicon. The result is systematic downcycling, where critical strategic materials are permanently contaminated or lost. What's more, the WEEE framework combines "preparation for reuse" and "recycling" into a single weight-based metric. Without independent targets for reuse, operators naturally opt for the cheapest treatment method rather than undertaking costly functional testing and refurbishment. Consequently, the domestic European reuse market remains virtually non-existent. Instead, large volumes of retired modules are exported to Africa and the Middle East under the guise of "second-hand equipment," which effectively constitutes disguised e-waste dumping.

Semi-structured interviews with eight experts confirm these three misalignments through the lens of practical operations. These insights reveal that a profound institutional lock-in sustains these dilemmas. In terms of stakeholder dynamics, PRO leadership is often dominated by importers whose primary commercial objective is minimizing compliance costs. This creates a systematic barrier to establishing specialized PV funds or adopting high-value recovery technologies. Finally, the extreme fragmentation of regulatory data and the absence of cross-sectoral verification prevent the effective tracking of waste flows within the industry's grey areas.

Recommendations

This thesis indicates that marginal adjustments within the WEEE framework cannot withstand the upcoming surge in PV waste. Consequently, the EU requires a fundamental governance transition focused on three areas: first, the complete separation of PV modules from WEEE into a dedicated legislative framework; second, a shift from a "Directive" to a directly applicable "Regulation" to resolve the legal fragmentation among 27 member states; third, the removal of B2B and B2C distinctions to ensure that utility-scale and commercial assets, comprising a large share of the market, are governed by a single, stringent compliance regime.

Building upon the above three changes, the thesis proposes a series of interventions measures spanning the entire lifecycle of PV modules:

Lifecycle Stage	Policy Intervention	Implementation & Rationale
Upstream	Digital Product Passports (DPPs)	Mandate comprehensive records of material composition and standardized dismantling guidelines to facilitate better EoL treatment.
	Eco-modulated Fee	Apply financial levels based on eco-design criteria to incentivize reliability and recyclability in module design.
Midstream	Independent EoL Trust Fund	Collect enough upfront treatment fees by a third party to guarantee capital availability after a 30-year lifespan.
	Special B2B Logistics	Deploy certified installers for on-site dismantling, preliminary testing and safe transport to enable functional reuse and high-value recovery.
Downstream	Standardized Reuse Certification	Establish technical thresholds and testing protocols for module reuse to curb illegal dumping and upscale domestic reuse market.
	Material-specific Targets	Replace weight-based metrics with mandatory recovery rates for critical materials to drive technological upgrades in recycling operations.
	Data Cross-verification	Implement comprehensive tracking mechanisms across producers, grid operators, PROs, recyclers and customs to ensure full traceability and eliminate grey market leakage.

In conclusion, PV modules are not merely another form of e-waste. They are strategic energy-generation assets that require holistic lifecycle management. Only by adopting these systemic paradigm shifts can the European Union covert the impending surge in PV decommissioning from a potential waste crisis into a strategic opportunity for critical raw material supply, thereby establishing a truly closed-loop circular economy for the solar industry.

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Abbreviations

AGEC – Anti-Waste for a Circular Economy Act (Loi Anti-Gaspillage pour une Économie Circulaire)

B2B – Business to Business

B2C – Business to Consumer

c-Si – Crystalline Silicon

CE – Circular Economy

CRMA – Critical Raw Materials Act

DfE – Design for Environment

DPP – Digital Product Passport

EoL – End-of-Life

EPR – Extended Producer Responsibility

ESPR – Eco-design for Sustainable Products Regulation

EVA – Ethylene-vinyl acetate

IEA PVPS – International Energy Agency Photovoltaic Power Systems Programme

IEEE – Institute of Electrical and Electronics Engineers

IRENA – International Renewable Energy Agency

JRC – Joint Research Centre

LCA – Life Cycle Assessment

PRO – Producer Responsibility Organization

PV – Photovoltaic

WEEE – Waste Electrical and Electronic Equipment

WSR – Waste Shipment Regulation

1 Introduction

1.1 Background

Photovoltaic (PV) technology represents a dual reality: it is the indisputable cornerstone of the global energy transition, yet simultaneously the source of a substantial future waste stream. As a key enabler for its goal of climate neutrality by 2050, solar energy is pivotal to the EU's ambition for an affordable, secure and sustainable energy future. Under the RePower EU Plan (European Commission, 2022), this ambition translates into rapid industrial expansion. By 2030, the EU aims to deploy approximately 750 GW of photovoltaic capacity[1], nearly doubling the 400 GW installed by the end of 2025 (SolarPower Europe, 2025).

However, this massive deployment creates an inevitable downstream challenge. As the current fleet of PV modules are about to retire and new installations multiply, the EU faces an impending "PV waste tsunami". Data from the Joint Research Centre (JRC, 2025) projects that the EU could face a cumulative PV waste of 6 to 13 million tonnes by 2040, a figure that is set to surge to between 21 and 35 million tonnes by 2050. A deeper examination by Yavuz et al. (2025), suggests that due to repowering, where operators systematically upgrade sites by replacing early generation modules with more efficient ones, the waste wave anticipated for 2050 could materialize 10-15 years earlier.

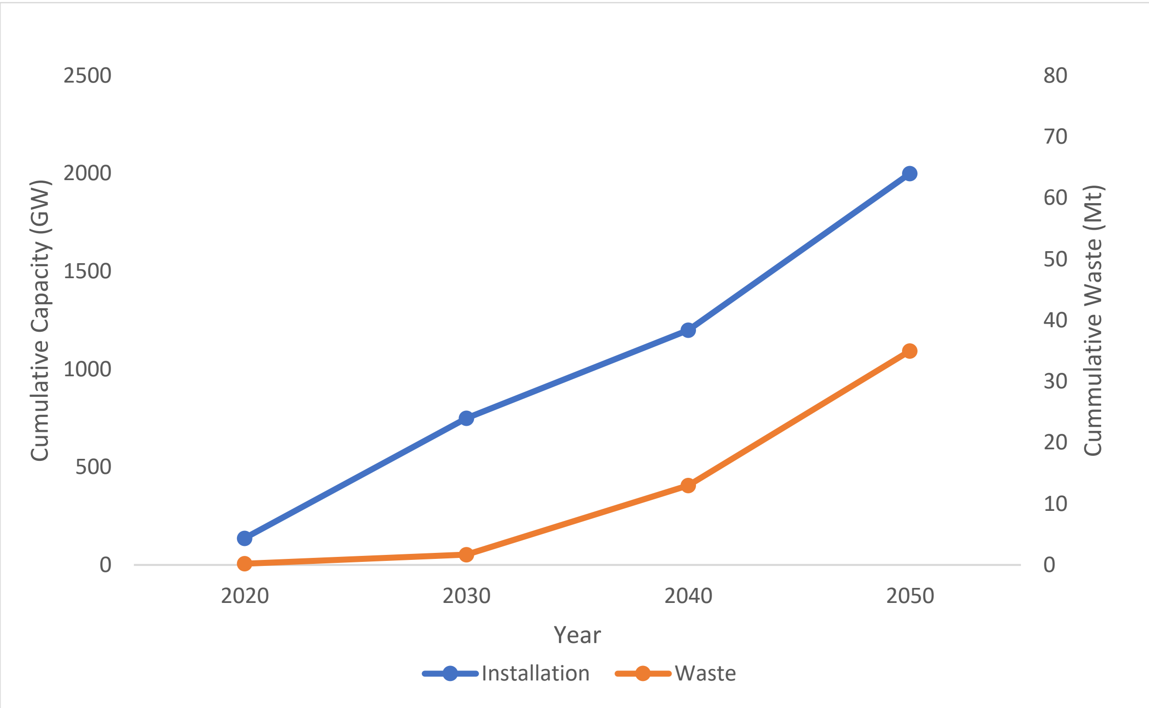

Figure 1-1. The Widening Gap Between PV Capacity and Waste Generation in the EU (2020-2050)

Note. Adapted from JRC (2025) and SolarPower Europe (2025).

Given their intrinsic nature as power generation devices, PV modules are classified as electrical equipment and fall within the regulatory scope of the Waste Electrical and Electronic

[1] Unless otherwise specified, all power capacity units (GW/MW) in this thesis refer to the Direct Current (DC) side, as this metric directly correlates with the physical volume of PV modules relevant for waste management analysis.

Equipment (WEEE) Directive (2012/19/EU).[2] Since the 2012 recast of this directive, PV modules have been officially grouped with consumer electronics, subjecting them to the principle of Extended Producer Responsibility (EPR). Producers bear the full legal and financial burden for collecting and treating their products at the end of their operational life. However, as illustrated in Figure 1-1, the long lifespan of PV modules creates a time lag between market entry and End-of-Life (EoL) management. The widening gap between PV new installations and waste generation suggests that the current rapid deployment is accumulating a massive stock of future waste that will soon flood the official management stream. Because the volume of PV waste has historically been statistically negligible and remains too small to be reported separately in some Member States today, the suitability of the WEEE Directive to govern this specific sector has rarely been scrutinized.

As this sector evolves from a niche category into a substantial waste stream, is a framework originally designed for household electronics truly capable of managing the scale and complexity of the EoL of PV?

1.2 Problem Statement

The core issue explored in this thesis is the fundamental structural mismatch between the WEEE Directive's standard compliance framework for short-lived consumer electronics and the physical and operational characteristics of PV modules as durable energy infrastructure.

The WEEE Directive operates on a pay-as-you-go financial mechanism and a volume-driven recovery model specifically designed to accommodate the high turnover rate of consumer appliances. Products, such as refrigerators and toasters, typically feature shorter lifecycles and easy collection and transportation within municipal networks. Furthermore, their EoL management is supported by mature processing technologies and steady economic returns from recovered materials and secondary markets (OECD, 2016). In contrast, PV modules function as long-term power generation equipment and critical energy infrastructure. Though their application scenarios are diverse, ranging from utility-scale power stations to distributed rooftop systems for private households, their underlying physical and economic features remain the same. Regardless of scale, PV modules are characterized by a long operational lifespan of 25 to 30 years, a high collection threshold due to complex dismantling and transportation requirements, significant potential for reuse and the high value in recovered materials such as silver and silicon (IRENA & IEA-PVPS, 2016). The divergence between consumer electronics and PV modules exposes the structural incompatibility within the current WEEE framework. This misalignment manifests specifically in financial mechanisms, logistical infrastructure and value recovery strategies.

[2] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE).

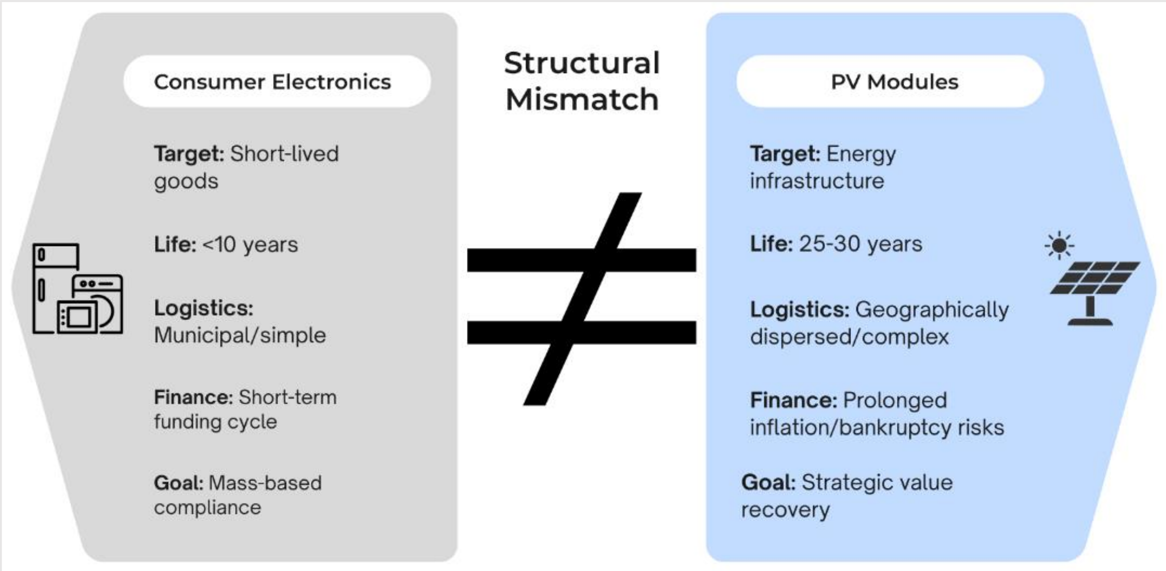

Figure 1-2. Structural Mismatch Between Consumer Electronics and PV Modules

First, the time lag between the installation and decommissioning of PV modules fundamentally invalidates the pay-as-you-go finance model. In standard WEEE framework, upfront fees are collected when products are put on the market. Fees collected today are utilized to finance the treatment of historical waste currently reaching its EoL and the future disposal of today's products relies on the continuous collection of fees from future sales. However, implementing this mechanism to PV modules with 30 years' lifespan creates severe financial vulnerabilities. Over such a distant endpoint, the collected funds are exposed to inflation, currency devaluation and corporate bankruptcy. This intergenerational time lag is highly likely to lead to financial deficits and the risk of orphaned waste, where the original producers no longer exist to bear the EoL management costs ((McDonald & Pearce, 2010; Sander et al., 2007).

Second, standard municipal collection infrastructure is inadequate for fulfilling the logistical requirements of PV systems, particularly in terms of their physical scale and operational environment. While consumer electronics can be easily deposited at local municipal collection points, decommissioned PV panels require specialized logistical operations. The removal of these modules from residential rooftops and remote utility scale farms demand strict safety protocols, skilled dismantling professionals and heavy transport equipment to prevent glass breakage and hazardous leaks ((Mahmoudi et al., 2021). Treating PV modules as household electronics waste overlooks the logistical complexity, imposing significant administrative and operation burdens on municipal authorities.

Third, the practice of assessing preparation for reuse and recycling rate by total weight directly hinders the comprehensive value recovery, destroying opportunities for secondary market reuse and sacrificing lightweight yet highly valuable materials. The WEEE Directive prioritizes recovery and recycling targets based on mass which encourages bulk processing and reduce the overflow of consumer electronics waste. However, applying weight-based targets to PV modules incentivizes the aggressive shredding of heavy bulk materials like glass and aluminum merely to be compliant, which physically destroys intact panels that could otherwise be redirected to secondary markets for reuse (Chhillar et al., 2025). As highlighted by Tao & Yu (2015), the true economic and environmental value of PV recycling lies in the recovery of critical materials such as silver and high purity silicon, and a regulatory focus on mere volume forces facilities into basic downcycling practices, resulting in the permanent loss of the economically important metals present in small quantities (Kastanaki & Giannis, 2022).

In summary, the discrepancies across financial, logistical and value-recovery dimensions demonstrate a structural mismatch within the current WEEE framework for managing the impending surge of EoL PV modules. Systematically evaluating the incompatibility across these various aspects is the core focus of this thesis. The primary objectives and the key research questions guiding this investigation are introduced in the following section.

1.3 Research Aim and Research Questions

Research Aim

This thesis aims to systematically evaluate the structural incompatibility between the standard consumer electronics compliance framework of the EU WEEE Directive and the physical characteristics of PV modules as durable energy infrastructure. To address the lack of an integrated perspective in existing literature, this research strives to construct a comprehensive policy roadmap to drive the transition of PV EoL management from a passive waste burden model to a proactive strategic value recovery process.

Research Questions

To achieve this overarching research aim, this thesis will explore the following three research questions. As detailed below, these questions guide the study from problem diagnosis to policy solution, systematically mapping out the specific inquiry, the required analytical approach and the key focus of each research phase.

Table 1-1. Summary of Research Questions and Chapter Focus

Research Question	Inquiry	Analytical Approach	Chapter Focus & Contribution
RQ 1 (Diagnosis)	What are the specific misalignments between the consumer electronics focus of the WEEE Directive and the actual operational realities of PV EoL management?	Literature Review Quantitative Analysis	The literature review established the regulatory baseline and identifies fragmented research regarding existing misalignments. The quantitative analysis then utilized secondary data to formally consolidate the findings into a comprehensive structural mismatch framework across financial, logistical and value-recovery dimensions.
RQ 2 (Impact)	How do these regulatory misalignments affect the current and projected EoL management of PV modules in terms of logistical efficiency, long-term financial viability, and strategic value recovery?	Quantitative Analysis Expert Interviews	The quantitative analysis and interviews utilize current and forecasted data to present the impacts of these misalignments on the operational realities of PV EoL management.

RQ 3 (Solution)	Which policy design options and regulatory pathways can best realign the EPR framework to transition from a waste management logic to a sustainable value recovery model?	Literature Review Expert Interviews	Based on the preceding analytical findings, Chapter 7 constructs a strategic policy roadmap and proposes actionable regulatory reforms to transition the current framework into a dedicated value recovery system

1.4 Scope and Limitations

The scope of this study mainly centers on the EU-level regulatory environment, specifically the implementation of the WEEE Directive. Materially, the thesis focuses on first-generation crystalline silicon (c-Si) PV modules. Since c-Si technology currently accounts for approximately 98% of the global market share (Fraunhofer ISE, 2024), it overwhelmingly dominates the imminent PV waste stream. Other technologies such as thin-film modules, possess different material compositions and are excluded from the main scope to maintain analytical depth. To ensure empirical depth, geographically, the thesis evaluates the performance of three representative Member States which include France, Germany and Sweden. These three countries are chosen because they each have a different approach in applying the WEEE Directive into national practice. The study covers a period of time from 2012, which was the year PV modules were officially integrated into the directive and extends until 2025. Analytically, the structural mismatch is examined through the financial, logistical and value-recovery aspects.

Several limitations should be acknowledged when interpreting the results of this study. Quantitative analysis is restricted due to the lack of separate historical data for PV waste, as it was often statistically invisible or combined within broader electronic categories. Projections such as future waste volumes and value recovery potential may be affected by unforeseen technological breakthroughs or changing market dynamics. Additionally, the qualitative insights are gathered from a group of 8 experts. While these interviewees represent key regulatory and industry roles, their perspectives might not reflect the reality of all 27 member states. This limitation applies also to the three countries selected. Furthermore, this study focuses on institutional and policy governance issues, not the technical engineering of recycling processes. Finally, the export of second-hand modules to markets outside of the EU may represent a significant future pathway for the EoL management of PV modules. However, this export scenario is not analyzed in depth as the final EoL treatment occurs beyond European jurisdiction. Though important, it would blur the focus of the core investigation of the thesis.

1.5 Thesis Outline

This thesis is structured into seven chapters that will guide the readers through the identification and analysis of the structural mismatch between the WEEE Directive and PV EoL realities.

Chapter 1 sets the stage by identifying the impending PV waste surge and defining the core research questions. Chapter 2 establishes the theoretical foundation through a three-dimensional lifecycle framework, mapping theories such as institutional path dependence and the waste hierarchy across the PV value chain to analyze the structural mismatches. In Chapter 3, the current regulatory landscape and academic and industrial research are reviewed. Chapter 4 details the sequential explanatory mixed-methods design, justifying the selection of France, Germany and Sweden as focal markets. The empirical work is contained within Chapters 5 and 6. The structural mismatch is identified and validated through secondary data analysis and expert insights. Lastly, Chapter 7 concludes the study by proposing a strategic roadmap for policy reform, offering comprehensive recommendations for transitioning toward a dedicated value recovery system for PV EoL management.

2 Analytical Framework

2.1 Overview of the Analytical Framework

This section illustrates the three-dimensional lifecycle governance framework presented in Figure 2-1. By using the physical flow of the PV module value chain as a baseline, this analytical matrix maps out the relevant theories alongside corresponding EU regulations and builds a solid theoretical foundation for the entire thesis. By applying these theoretical lenses, readers can better understand why the structural mismatch occurs and why a systemic reform is needed for the regulatory management of PV EoL.

This framework is grounded in the physical flow of PV modules within real-world commercial settings. The PV module lifecycle in the middle layer is divided into three distinct phases. The upstream phase includes raw material sourcing, module manufacturing and cross-border imports. The midstream phase covers market entry and a prolonged operational lifespan of 25 to 30 years. The downstream phase focuses on the collection and quality assessment of retired panels. From this point, it branches into two distinct EoL treatment pathways. One is the realistic physical dismantling driven by current compliance rules. The other represents an ideal, high-value circular route capable of truly closing the industrial loop. The horizontal value chain allows for the precise identification of where the implementation of environmental policies clashes with industrial realities.

Extending from the value chain forms the theoretical foundation of this study. The Circular Economy (CE) concept, along with its tailored PV-specific R-strategies, serves as an overarching umbrella that covers the entire lifecycle. They provide the macro-level strategic guidance. At the same time, specific analytical theories are matched to the three lifecycle phases. For example, the Design for Environment (DfE) theory is applied to the upstream phase. Institutional Path Dependency covers both the midstream and downstream phases. Finally, the Waste Hierarchy Principle and Value Retention Theory are embedded within the downstream stage to provide direct theoretical guidance for PV EoL management.

The bottom layer represents the core EU regulations that impose binding constraints on the industry across different lifecycle stages. Beyond the WEEE Directive, which is the main focus of this thesis, this tier also incorporates the Eco-design for Sustainable Products Regulation (ESPR)[3], the Critical Raw Materials Act (CRMA)[4] and the Waste Shipment Regulation (WSR)[5] which is related to the export of used modules as second-hand products. When read vertically,

[3] Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products.

[4] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials.

[5] Regulation (EU) 2024/1157 of the European Parliament and of the Council of 11 April 2024 on shipments of waste.

it creates a direct visual contrast between the theories and specific institutional mandates. This layer also lays a clear logical groundwork for the legal landscape analysis in Chapter 3.

In summary, this three-dimensional matrix weaves together the macro visions, micro theories, PV physical realities and foundational regulations. Drawing inspiration from the existing literature and insights from expert interviews, these specific theoretical concepts are selected to address the practical need to explain the regulatory challenges at each stage of the PV lifecycle. First, the CE and PV-specific R-strategies are chosen to establish a clear baseline for what an ideal closed-loop management system should achieve. Second, the DfE theory is included to explain a physical contradiction. Manufacturers design panels to survive decades of harsh weather, which directly conflicts with the downstream need for easy dismantling. Third, Institutional Path Dependency is applied to explain the current policy lock-in. It clarifies why PV modules were placed under the WEEE Directive and why this management system resists to change. Finally, Value Retention and the Waste Hierarchy Principle evaluate the actual downstream processing. These concepts provide a direct theory-backing to criticize the current weight-based compliance rules, showing why simple mechanical shredding wastes valuable resources. Together, these complementary theories and principles allow the thesis to systematically diagnose the technical, administrative and economic causes of the structural mismatch. The following three sections will elaborate how these theoretical lenses expose the profound challenges that the WEEE Directive faces when governing long-life energy infrastructure.

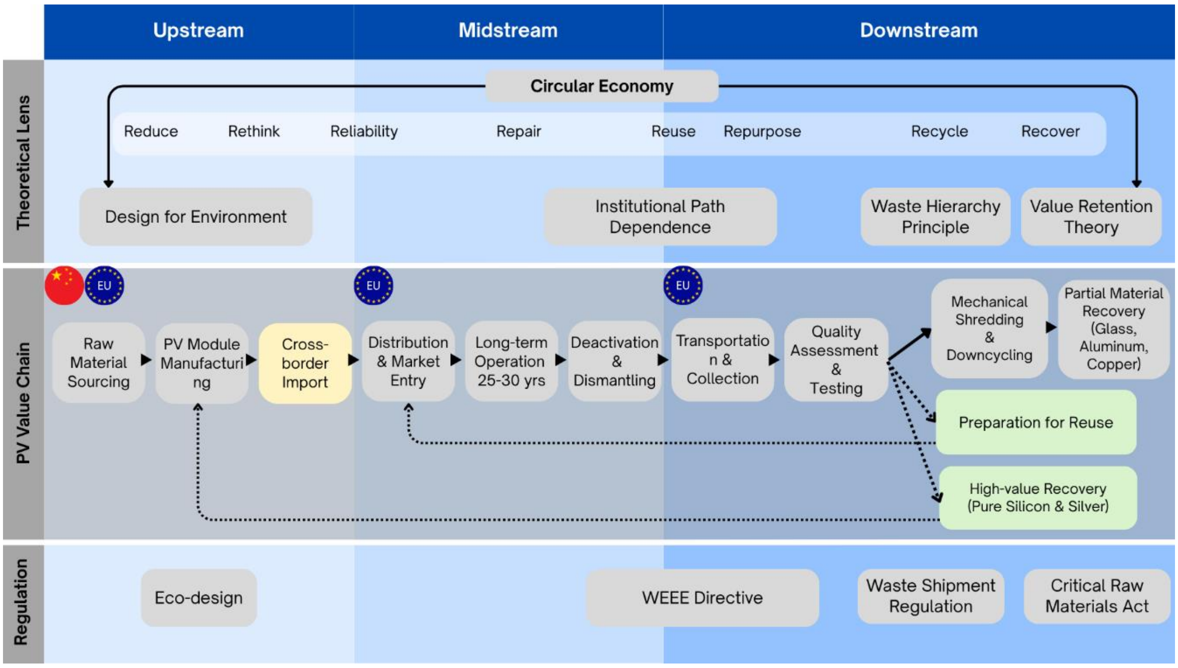

Figure 2-1. A Three-Dimensional Lifecycle Governance Framework for PV Modules

Note. Adapted from Nyffenegger et al. (2024) and Mirletz et al. (2022).

2.2 The Macro Vision: Circular Economy and PV-Specific R-Strategies

Under the EU's 2050 climate neutrality goal, the massive deployment of the PV sector is the key pillar for energy transition. However, as a material-intensive industry, depending on a traditional linear consumption model is unsustainable. In the interest of long-term environmental and economic viability, the circular economy has evolved from a mere environmental vision into an essential strategic framework for PV lifecycle governance.

A circular economy operates as an industrial system that is restorative and regenerative by design (Ellen MacArthur Foundation, 2013). It seeks to intentionally design out waste. By doing so, it replaces the conventional linear EoL concept with the continuous restoration, retention and circulation of resources (Kirchherr et al., 2017). Regarding the solar sector, applying CE principles means that first, the industry must maximize the physical lifespan of existing energy infrastructures through direct system maintenance and repair and reuse. Later, when modules completely lose their operational capacity, the retired panels should be treated as urban mines rich in critical resources. Extracting high-value materials from these panels directly secures EU's supply chains and stipulates the green transition of domestic manufacturing (Nyffenegger et al., 2024).

To create a complete closed loop from resources to products and back to secondary materials, CE theory establishes the 4R principles, including Reduce, Reuse, Recycle and Recover. To address the unique nature of PV products, the Institute of Electrical and Electronics Engineers (IEEE) have proposed a dedicated set of R-strategies for PV. As illustrated in Figure 2-1, this thesis selects 8 PV-specific R-strategies from the IEEE model (Mirletz et al., 2022). They can be categorized into three strategic levels based on their primary environmental and economic goals:

Level 1: Design Optimization

- **Reliability**: manufacture high quality modules with extended service lives to postpone waste generation.
- **Rethink**: focus on systemic design for repair and reliability; ensure future-proofing by allowing modern components to integrate seamlessly with older infrastructure.
- **Reduce**: minimize energy, material and carbon inputs during production.

Level 2: Maximize Net Energy Generation

- **Reuse**: resell functional modules in secondary markets to extend the service lives of modules.
- **Repair**: on-site maintenance and replacement of components to restore optimal power generation.
- **Repurpose**: utilize degraded modules in alternative systems with lower performance requirements, such as off-grid applications or agricultural shading.

Level 3: Turn Waste into Feedstock

- **Recycle**: separate components to retrieve high-purity materials like silicon and silver for use in new production cycles.
- **Recover**: energy recovery via incineration for residual materials.

2.3 Limitations of Upstream Intervention: Design for Environment

DfE is a holistic engineering method that builds environmental considerations into the very beginning of product development. The goal is to minimize ecological damage through the entire product life by refining material choices and structural design (Bovea & Pérez-Belis, 2012). In Europe, this concept is operationalized through the Eco-design for Sustainable Products Regulation (ESPR). It serves as a framework regulation that establishes the general mechanisms and principles for setting eco-design requirements. The key objective is to integrate environmental considerations into the initial product development stage to minimize negative ecological impacts through the entire product life cycle. (European Parliament and the Council of the European Union, 2024). PV products are included in the First Working Plan of the ESPR for the period 2025-2030 and are classified under the energy-related products category. The delegated act targeting such products is expected to be officially adopted sometime between the end of 2026 and 2027 (European Commission, 2024). Based on the previous disclosed working priorities, future regulation for this category is expected to expand beyond energy performance to include specific circularity requirements. These measures involve mandatory carbon footprint limits and declarations, product design for long-term reliability and durability, repairability and recyclability, mandated Digital Product Passports (DPPs) that tracks the entire lifecycle data of PV panels (UL Solutions, 2024).

However, the practical application of this eco-design concept to the PV sector may face challenges. First, mainstream solar panels function as outdoor energy infrastructure designed for decades of continuous operation. To guarantee long-lasting physical reliability and resistance to extreme weather, irreversible encapsulation materials such as ethylene-vinyl acetate (EVA) films are used to permanently bond the internal solar cells to the outer glass panels. This structural design creates a fundamental engineering contradiction between the durability required for a prolonged service life and the non-destructive dismantling at the EoL stage advocated by circular design principles (Schnatmann et al., 2022a).

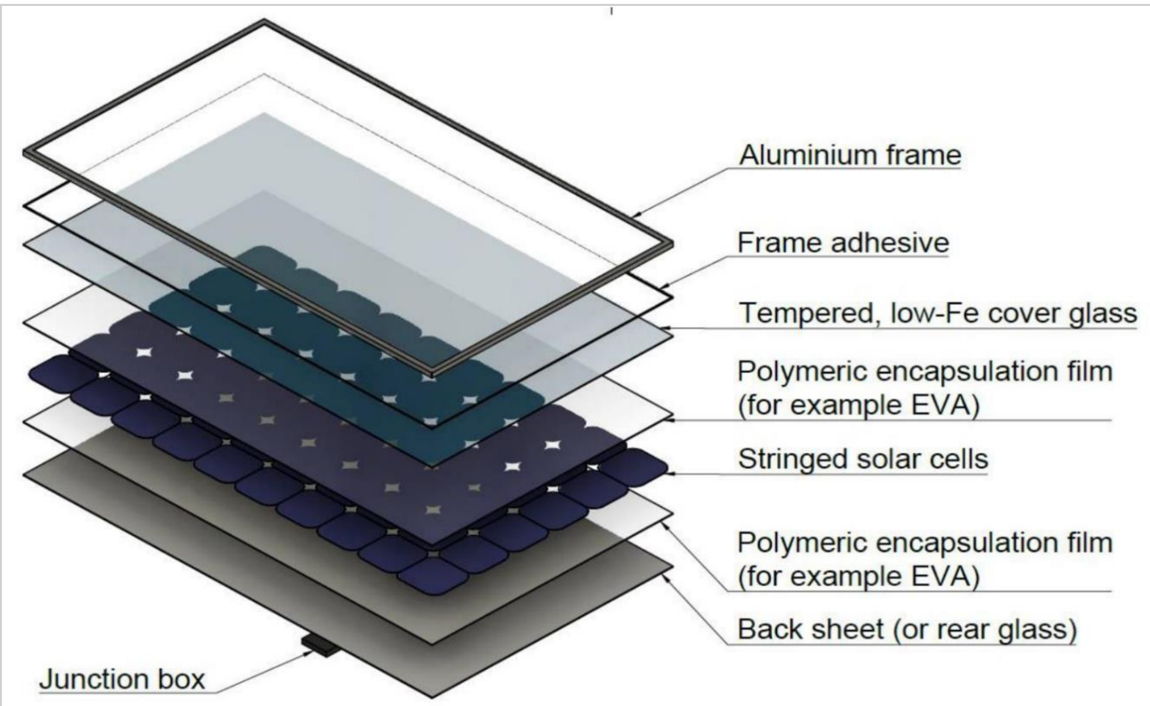

Figure 2-2. Structure of the Mainstream c-Si PV Modules

Note. Reprinted from Schnatmann et al. (2022b)

Second, from the supply chain perspective, the vast majority of PV module manufacturing and critical raw material extraction occur outside of Europe. Mandatory DPPs and carbon footprint declarations would force PV manufacturers entering the EU market to track and verify granular material data across extended transnational supply chains. Without a universal global standard, efforts to acquire this cross-border data solely for EU compliance may face setbacks due to sensitive commercial confidentiality issues and substantial administrative costs (Walden et al., 2021).

2.4 Systemic Lock-in: Institutional Path Dependency

When examining the structural mismatch of WEEE in managing PV EoL, two questions emerge. Why were solar modules initially categorized under the WEEE Directive, given that solar modules generate electricity instead of consuming electricity? Also, since there are obvious limitations of WEEE in managing durable solar modules, why has the EU not yet made changes in policy design? To address these two questions, this thesis introduces the theory of institutional path dependency. The main idea of this theory is that once an initial policy choice or institutional design is established, it generates increasing returns and mutually reinforcing mechanisms within the system (Pierson, 2000). As time progresses, various stakeholders align their investments and behavioral patterns with the established trajectory. As a result, the entire system falls into a locked-in state (North, 1990). Under such conditions, even when the original institution proves to be inefficient, the transition costs are too high for reforms to be carried out.

During the revision of the WEEE Directive in 2012, a core legislative shift was the transition from a "closed scope" to an "open scope" principle, aiming to cover all electrical and electronic equipment. EU acknowledged the potential risk of surging PV waste but at that time, actual retired volumes were statistically negligible. For policymakers, drafting a dedicated legislative framework exclusively for PV waste was deemed administratively impractical and disproportionately costly. Incorporating PV modules into the established WEEE framework under the large equipment category was a low-cost and efficient administrative shortcut (Department for Business, Innovation and Skills (UK), 2013). This choice illustrates perfectly the concept of an initial incidental choice in path dependence theory. Although this decision seemed convenient at the time, it ultimately takes the entire governance system to a rigid path that is difficult to change.

This categorization systematically locks the PV industry into the WEEE framework across legal, financial and cognitive dimensions. First, in terms of the legal and administrative aspect, EU Member States spent years in translating the WEEE Directive into domestic transpositions and building extensive national registration and compliance systems. Having committed substantial sunk cost to build this bureaucratic infrastructure, national authorities are deeply locked into the established trajectory. As a result, any major regulatory changes specifically tailored to managing PV EoL are likely to incur high transition cost. As Pierson (2000) explains, the high fixed costs associated with establishing an initial administrative system make subsequent policy reversals or radical departures structurally difficult. Second, regarding financial and business models, PROs and associated recyclers have fully adapted to the weight-based compliance matrix. Heavy investments have been put on the crude mechanical shredding equipment and long-term logistics contracts with municipal collection networks. If the policy shifts the focus towards high-value recycling or functional reuse, the accumulated sunk costs would be largely wasted. The vested stakeholders would undoubtedly resist any radical restructuring (Nyffenegger et al., 2024). Finally, at the cognitive level, after more than 10 years' implementation, legislators and municipal systems have become accustomed to viewing solar modules as large electronic waste, thereby neglecting their strategic nature as long-lasting energy infrastructure.

To summarize, the current challenges in the financial, logistical and high-value recovery aspects in PV EoL governance are not due to mismanagement but rather the inevitable outcomes of a deep-seated system lock-in. This theoretical lens lays a solid foundation for the empirical analysis in the subsequent chapters. It indicates that marginal adjustments within the existing WEEE framework are not enough. To truly unlock the circular potential of retired panels, policymakers must move beyond the current system's resistance and pursue a paradigm shift in future regulatory approaches.

2.5 The Value Conflict: Waste Hierarchy and Value Retention Theories

The Waste Hierarchy underpins EU's waste law and circular economy governance. This principle prioritizes waste management pathways based on their environmental benefits. The hierarchy ranks these options as prevention, preparation for reuse, recycling, other recovery and finally disposal (European Parliament and of the Council of the European Union, 2008). Value retention theory emphasizes the importance of systematic interventions throughout a product's lifecycle. The goal is to preserve the original manufacturing inputs, engineering attributes and material value embedded within the product for as long as possible (Reike et al., 2018).

Translating these theoretical value retention priorities into regulatory practice requires a dual focus on both whole-module reuse and critical material recycling. At the reuse stage, the EU WSR and the Annex VI of the current WEEE Directive jointly establish strict requirements for the transnational export of second-hand PV modules. These regulations require exporters to provide professional testing and certification to prove the equipment remains fully functional. The aim of these regulations is to prevent electronic waste from leaking into regions lacking proper environmental treatment capabilities under the disguise of equipment reuse (European Parliament and Council of the European Union, 2012, 2024a). These legislative measures, however, mostly serve as defensive barriers against illegal dumping. They do not proactively recognize or stimulate the true economic value of the second-hand solar market. What's more, there is no detailed and universal technical guidance on the specific testing methodologies and certification standards required to scale up the reuse economy, causing the solar resale market to become a grey area in Europe. Relevant to material retention, CRMA lists high-purity silicon as a critical material vital to European strategic security and mandates an increase in internal regional recycling rates for this element (European Parliament and the Council of the European Union, 2024b). Although silver is not on the list, its high value in the current market makes it the core driver for solar panel recycling.

The intersection of these two concepts offers clear guidance on maximizing the value of decommissioned PV modules. When solar modules are about to retire, the primary task of systemic intervention is to prepare the modules for reuse through professional testing and certification in order to maximize the energy generation function of the equipment. Panels that cannot enter the reuse stream should then be processed with advanced separation technologies to extract pure silicon and silver to achieve high-value recycling. This tiered value retention model prioritizes the protection of physical forms before extracting the material base. It ultimately serves as the key theoretical solution to correct the current dilemma of crude shredding method.

3 Literature Review

3.1 Literature Search Strategy and Methodology

The thesis employs three methods to systematically gather relevant literature. First, keyword searches were used to establish a foundational body of research. Second, a snowballing technique was applied to discover additional critical studies through the reference lists of the initially gathered papers. Finally, given the practical nature of the study and the need for quantitative data to capture actual market dynamics, the review also integrates a substantial amount of grey literature such as publications from research institutions and solar industry reports.

Initial Keyword Search

The initial literature search was conducted within the Scopus database using two keyword combinations. To ensure relevance, the results were restricted by disciplinary filters, limiting the scope to Energy, Environmental Science, Social Science, Decision Science and Business Management. The first combination, ("Photovoltaic" OR "PV module") AND ("WEEE Directive" OR "Directive 2012/19/EU" OR "Recast Directive"), yielded 19 papers. The second query, ("Photovoltaic" OR "Solar panel") AND ("Extended Producer Responsibility" OR "EPR" OR "Take-back scheme" OR "Collection cost" OR "Recycling fee"), identified 69 papers. Following a thorough screening and data cleaning process, 42 key publications were selected for further analysis.

Snowballing

As the in-depth review of the initial papers progressed, additional studies naturally emerged from their reference list. This led to the organic adoption of a snowballing method to ensure these omitted publications were fully incorporated into the review.

Grey Literature

Finally, due to the high degree of policy relevance, the research incorporated critical industry reports and official documents. Key sources included technical reports from the International Energy Agency (IEA PVPS), renewable energy outlooks from International Renewable Energy Agency (IRENA), and annual operational reports from national PROs such as Soren in France, Stiftung EAR in Germany, and El-Kretsen in Sweden.

The final selection consists of approximately 60 key documents that provide the theoretical and empirical basis for this study. These sources are categorized in Table 3-1.

Table 3-1. Distribution of Reviewed Literature and Key Data Sources

Category	Sources	Approx. Count	Contribution to the Thesis
Regulations and legal frameworks	EU Directive 2012/19/EU EPR National transpositions of France, Germany and Sweden	~10	Establishing the legal baseline, compliance requirements and regulatory history of the WEEE Directive
Academic Journals	Peer-reviewed articles in Energy, Environmental Science, Social Science and Business Management disciplines	~40	Providing technical assessments, economic feasibility models and critical theories on EPR and institutional mismatch

Industry and Institutional Reports	IEA PVPS, SolarPower Europe, JRC and national PRO annual reports	~18	Offering current market data, waste volume projections and operational performance metrics

To systematically unpack the complexities of PV EoL management, the following review is structured into three dimensions. Section 3.2 establishes the regulatory landscape by examining the EU framework and the selected national transpositions. Section 3.3 evaluates the prevailing research focus within peer-reviewed literature. Section 3.4 then bridges the gap between mainstream academic discourse and empirical reality by introducing institutional grey literature. Collectively, a comprehensive literature foundation is built to identify the research gap and investigate the structural mismatch central to this thesis.

3.2 The Regulatory Landscape: EPR & WEEE Directive

Extended Producer Responsibility is defined as an environmental policy principle that extends a producer's physical, financial and informative responsibility for a product to the post-consumer stage of its lifecycle (Lindhqvist, 2000). In practice, physical and financial responsibilities aim to internalize the external environmental costs of EoL management, shifting the burden from municipalities to producers to correct market failures. The informative responsibility requires manufacturers to provide recyclers with vital data regarding product components and the location of hazardous substances, which is essential for ensuring safe and efficient treatment processes. Rooted in the "polluter pays" and prevention principles, EPR intends to leverage the manufacturers' knowledge of their own products to trigger innovations in waste collection while mandatory recovery targets help secure a steady flow of secondary materials to build viable recycling markets (Dalhammar, 2018). Theoretically, this framework should incentivize manufacturers to integrate eco-design into their product development, as noted by Tojo (2004), who argues that mandatory EPR programs have a positive impact on sustainable design strategies, especially when individual producers are held explicitly responsible for their own products.

While EPR models have achieved relative success in managing standard consumer electronics, its currently dominant collective compliance mechanism has been heavily criticized for its inability to ensure long-term financial continuity (Mayers et al., 2013; van Rossem et al., 2006). Within most collective compliance schemes, producers pay an average fee based on their current market share rather than the actual future disposal costs of their own products. Such a model blurs individual producer responsibility and leaves the system without enough dedicated capital for products with long operational lifespans, making the entire mechanism vulnerable to future financial fluctuations (Dalhammar, 2018). Simultaneously, general EPR frameworks remain inherently susceptible to the accumulation of "orphan products", a phenomenon occurring when original manufacturers exit the market or declare bankruptcy, thereby leaving the EoL management costs without a legally liable bearer (Monier et al., 2014). The dilution of responsibility caused by the average fee mechanism and the shifting of financial burdens from orphan products collectively constitute the core challenge to the financial sustainability of the current EPR operations.

When applied to PV modules, this flaw is magnified by a significant time gap, as solar panels serve for over 25 to 30 years. Buehler (2019) points out that orphan waste emerges when panels are produced by companies that are no longer in business and therefore cannot be held responsible for their disposal. This time gap breaks the financial continuity of conventional EPR models, ultimately shifting the massive disposal costs of these orphan products onto municipal authorities or taxpayers and defeating the "polluter pays" principle, and this presents a problem for an industry whose products have a very long lifespan.

WEEE

The WEEE Directive acts as the primary legislative framework that translates the EPR concept into mandatory legal obligations across the EU. Established to mitigate the environmental impacts of rapid electronic consumption, the Directive requires the systematic collection, treatment and environmentally sound disposal of electrical waste. At the operational level, the Directive requires member states to establish national registers. All producers should register prior to placing new equipment on the market. To directly address the previously discussed risk of orphan products, the framework mandates an upfront financial guarantee from the producers. The guarantee may take the form of participation by the producer in appropriate schemes, a recycling insurance or a dedicated blocked bank account. Alongside these financial commitments, a defining characteristic of the regulatory approach is its reliance on weight-based metrics to evaluate operational compliance. Minimum recovery and recycling rate targets are established for the various equipment categories (European Pafrorliament and Council of the European Union, 2012).

Producer Responsibility Organizations (PROs) serve as the collective legal entities that take the regulatory obligations for their members. They pool resources to arrange waste collection, tender contracts to specialized recycling facilities and ensure that the weight-based recovery targets set by the Directive are met. To finance these extensive range of works, members are required to pay an annual administrative membership fee alongside a volume-based eco-contribution for every new unit placed on the market. This scheme operates on a "pay as you go" financial model. Current waste management costs are divided proportionately according to each producer's present market share, meaning that the capital collected from current market placements is immediately utilized to finance the collection and treatment of historical waste currently reaching end of life (Atasu et al., 2010). Given the financial inefficiency of holding large cash reserves in the locked account for decades and the operational ease of meeting compliance targets collectively, most enterprises opt to join a PRO. Empirical data confirms that collective compliance schemes consistently capture over 95% of the registered market share across mature European regulatory environments (Baldé et al., 2020).

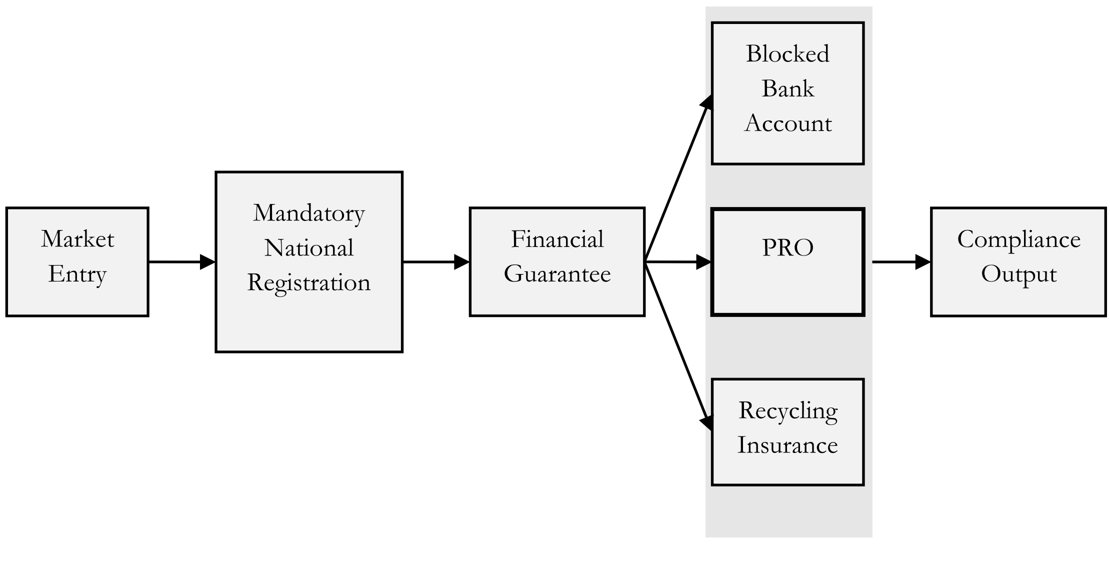

Figure 3-1. Schematic Overview of the WEEE Directive Compliance Pathways

The integration of PV modules into the WEEE Directive defines the specific classification and responsibility allocation that producers must observe. In 2012, through the WEEE Directive recast (Directive 2012/19/EU), PV modules were formally included in the legal framework due to the forecast of massive future waste volumes. Instead of establishing a dedicated regulatory category for the unique material composition and decades-long lifespan of solar panels, the Directive classified PV modules under the broad category of large equipment. Consequently, PV modules are subject to the standard weight-based performance metrics with an 85% minimum overall recovery rate and an 80% preparation for reuse and recycling rate (European Parliament and Council of the European Union, 2012).

The Directive further refines these obligations by distinguishing between waste from private households, commonly categorized as business-to-consumer (B2C) and waste from users other than private households, hereafter referred to as business-to-business (B2B). For B2C installations, producers bear a mandatory financial responsibility to the product EoL management. However, in accordance with general provisions for business-to-business equipment, the Directive provides a contractual mechanism for commercial deployments, enabling producers to transfer waste management responsibilities to professional users through private agreements (European Parliament and Council of the European Union, 2012).

To mitigate orphan waste risks, the framework sets a distinction between historical and new PV waste. While the 2012 Directive initially imposed retroactive liability on products sold after 2005, this provision was revoked in 2022 by the Court of Justice of the European Union for violating the principle of legal certainty, which dictates that legal obligations must be foreseeable and should not impose retroactive financial burdens on past actions (*VYSOČINA WIND a.s. V Česká republika – Ministerstvo životního prostředí*, 2022). Following this judicial intervention, the official timeline was revised to establish August 13, 2012 as the definitive threshold for financial responsibility. Consequently, PV panels placed on the market after this date are classified as new waste, for which individual producers bear direct financial liability. In contrast, panels deployed before this threshold are designated as historical waste. The disposal costs for such historical waste are shared proportionately among all active market participants based on their current market share (European Parliament and Council of the European Union, 2024).

The WEEE Directive has yielded remarkable environmental achievements across the EU but not without incurring a number of operational challenges. It successfully translates the theoretical concept of EPR into binding legislation, compelling electronics manufacturers to internalize the disposal costs of their goods. This institutional pressure leads to the establishment of Europe-wide collection networks and diverts massive quantities of hazardous waste from municipal landfills (Salhofer et al., 2016). Parallel to the infrastructure development, it motivates the producers to integrate sustainable eco-design features into their products (Lambert, 2012). The framework has been criticized for some operational flaws as well. One major academic critique is the legislation’s rigid dependence on weight-based compliance metrics. Measuring recycling success purely by mass incentivizes the operators to recover heavy bulk materials while losing trace amounts of highly valuable critical metals to low-grade downcycling (Richter, 2019). The framework also exhibits profound financial vulnerabilities. Decentralized PROs struggle constantly with market free-riders and remain ill-equipped to fund the management of orphan products left behind by bankrupt producers (Bressanelli et al., 2020).

National Transpositions for PV EoL Management

The WEEE Directive acts as the fundamental legal baseline for electronic waste management across the EU. Member states, based on this overarching framework, draft their own national laws, taking the responsibility of specific operational details such as setting up the administrative bodies, structuring financial mechanisms and organizing logistical networks. France embeds its electronic waste regulation within the Environmental Code (Code de l'environnement), Germany established its Electrical and Electronic Equipment Act (ElektroG) to govern this sector and Sweden operates under the Ordinance on Producer Responsibility for Electrical and Electronic Equipment (Förordning 2014:1075). Given the administrative discretion permitted by the WEEE Directive, these three countries show distinct operational characteristics in the EoL management of PV modules. It is necessary to explore the regulatory and operational differences as it not only provides the empirical foundation for the structure mismatch discussed in this thesis but also offers practical inspirations for guiding future policy reforms.

France

France adopts the Directive into binding domestic law through its Environmental Code (Code de l'environnement). PV modules are explicitly classified as Category 7 electronic waste and thereby legally binding to strict EoL management obligations (République Française, 2023). The French legislation shows a strong tendency towards centralized liability. In contrast to the WEEE Directive's separation of responsibility between B2C and B2B producers, the French law explicitly allows the solar industry to merge both household and commercial PV waste into a single compliance system. This design significantly reduces the administrative friction associated with multiple registrations. Regarding the timeline for historical waste and the definition of orphan products, the law strictly enforces the legal boundary of August 13, 2012. The state mandates that environmental liability never remains unassigned for solar assets placed on the market before this date or left behind by bankrupt manufacturers. The legal provisions explicitly require all active PV producers to share the processing costs of these orphan wastes collectively based on their current market share (Soren, 2024a).

Moving to practical operations, France operates a classic centralized governance structure. The national government grants exclusive authorization to a single non-profit PRO named Soren (previously known as PV CYCLE) to coordinate all PV recycling activities across the country. All PV producers and importers entering the French market are required to join this organization. In terms of the financial mechanism, Soren operates on the "pay-as-you-go" model to secure funding. The invoice for every new panel sold must display a visible environmental fee. Soren then uses the funds collected now to cover the recycling costs of old panels currently reaching their end of life. This intertemporal subsidy mechanism serves as the main financial tool for bridging the funding gap for historical orphan waste. On the logistical aspect, Soren has built a highly adaptable collection network. Owners of small-scale private roof installations can drop off their panels free of charge at partnered municipal collection points or electrical wholesalers. For large commercial solar farms reaching specific tonnage thresholds, Soren directly sends specialized transport fleets to the sites for bulk removal. These panels are then dispatched to contracted advanced treatment facilities to ensure deep material recovery (Defrenne, 2024). To fulfill the strict national mandates of an 85% overall recovery rate and an 80% physical recycling rate, Soren requires its partners such as Veolia to operate independent processing lines dedicated to PV in order to efficiently separate solar glass and silicon (Veolia, 2018).

Germany

The national transposition of the WEEE Directive in Germany is enacted through the Electrical and Electronic Equipment Act (ElektroG). Unlike France, which creates a standalone category specifically for PV modules and puts both B2B and B2C modules under the same regulation, the German law places PV modules into a broader Category 4 for large general equipment. ElektroG separates B2C and B2B equipment based on the dual-use principle, which dictates that any device capable of being used in both private and commercial settings defaults to a B2C classification. If the power output, dimensions and installation requirements of a solar panel make it entirely possible for use on a standard residential roof, the law classifies it as B2C equipment. This applies even if the producer sells these panels in bulk to commercial installation companies. Only industrial-grade modules designed for large solar farms or utility-scale grids can be legally seen as B2B assets, as their technical complexity completely excludes them from being installed by private households. Germany adopted this legislation relatively late regarding the timeline for historical waste. The law mandates October 24, 2015 as the official boundary for including PV modules into the national environmental responsibility framework. Any equipment placed on the market before this date is classified as historical waste (Bundesministerium der Justiz, 2024). Germany has adopted a decentralized competitive model for electronic waste governance. At the core of this model is a national authority called Stiftung EAR, serving as its central coordinating body. This unique institution completely avoids handling any physical recycling operations and does not maintain any centralized funding pool. It functions as an administrative clearinghouse to coordinate data and commands. The fulfillment of compliance is pushed to the private market (IRENA & IEA-PVPS, 2016).

At the practical operational level, the German ElectroG creates a high-cost compliance environment through its strict equipment classification and decentralized market-based recovery mechanism, which collectively drives up administrative expenses and incentivizes e-commerce free-riding. For B2B PV modules, the law grants high commercial freedom. Producers do not need to pay any upfront funds to the state. They only need to submit a written document proving that a clear take-back plan has been made within the company. For B2C panels, producers must provide an insolvency-safe financial guarantee every year. Companies are forced to lock their future recycling funds into bank trusts or insurance policies decades in advance. This massive amount of capital can only be released after the product reaches its EoL and the company has fulfilled its recycling obligations. On the logistics side, Germany relies on widely dispersed municipal collection points. From there, Stiftung EAR, acting purely as an administrative clearinghouse, uses a complex algorithm to issue pick-up orders to producers based on their respective market shares (Rotter et al., 2011). The combination of algorithmic dispatching, free market bidding, complicated registration and long-term financial lock-in creates a significant compliance barrier. This complexity has caused cross-border e-commerce speculators to evade registration and shift the heavy burden of recycling responsibilities entirely onto compliant domestic firms (Hiltonne et al., 2019).

Sweden

At the national regulatory level, Sweden governs PV waste through the Ordinance on Producer Responsibility for Electrical Equipment (Förordning 2022:1276), with the entire system operating under the supervision of the Swedish Environmental Protection Agency. The Swedish model is a typical WEEE implementation that is semi-centralized and municipal-centric. Like Germany, Swedish law puts PV modules into Category 4, large general appliances. In terms of B2B and B2C definitions, the Swedish law applies a strict legal concept known as the "dual-use" rule. The underlying logic is: if a product can technically be used by both private households and commercial entities, it must be regulated as a B2C product. Any panel with physical dimensions and technical characteristics suitable for standard residential rooftop installation automatically defaults to a B2C consumer device. This classification applies regardless of the actual purchasing entity. To secure B2B commercial exemption, producers must submit detailed engineering documentations proving that the equipment is exclusively designed for large-scale, professional fixed installations. Regarding historical waste, Sweden aligns completely with the WEEE Directive and sets August 13, 2012 as the statutory cutoff date (Regeringskansliet, 2022). To circumvent the severe administrative and financial burdens, producers typically opt for

PROs to assume their recovery obligation. In Sweden, the most influential PRO is El-Kretsen that holds an absolute dominant position with a 99% market share nationwide (Forrest & Hiltonne, 2019).

When it comes to physical implementation, joining PROs completely spares companies from the severe burden of locking in massive amount of future capital. For logistics, Sweden relies heavily on its well-developed municipal recycling centers. Consumers and local installers deliver decommissioned modules to these collection points and then the PRO acts as a central dispatcher and hires private logistics fleets to transport the waste to contracted treatment facilities for final recovery. This dependence on municipal collection points leads to a logistical problem, as these sites were originally intended for household electronic waste, not for bulky and fragile laminated glass panels. Solar panels are mixed with other electronic waste and are stacked during transportation, causing widespread shattering. As a result, fully functional panels lose chance for lifespan extension (Axfoundation, 2025). Beyond the physical logistical damage, since Swedish follows strictly the 80% weight-based recovery target, recyclers routinely utilize direct mechanical shredding. This method allows them to cheaply extract heavy glass and aluminum frames to meet the quotas. Ultimately, this pure weight-driven compliance model systematically incentivizes low-grade downcycling regardless of the initial equipment condition, completely destroying the valuable internal silicon architecture and resulting in an irreversible loss of critical resources (Auer, 2015).

Table 3-2. Comparative Analysis of WEEE Transpositions for PV modules

Dimension	France	Germany	Sweden
Governance Structure	Centralized Exclusive state-authorized monopoly	Decentralized Competitive market with administrative clearing house	Semi-centralized Dominant collective organization with municipal integration
Equipment Classification	Dedicated category for PV modules Unified B2B and B2C compliance system	General category Strict separation of B2B and B2C compliance system	General category Strict separation of B2B and B2C compliance system
Financial Guarantee	Mandatory collective guarantee Mandatory participation in a single fund pool	Strict individual guarantee Mandatory long-term capital lock-in for each producer	De facto collective guarantee Market-driven consolidation into a single fund pool
Logistical Strategy	Independent network Specialized PV-only treatment lines	Algorithmic dispatch Random municipal pick-up orders for producers.	Municipal-Integrated Reliance on existing household e-waste infrastructure.
Systemic Friction	Stability risks Total dependency on a single entity's efficiency.	Market evasion High barriers incentivize free-riding and speculators	Logistical mismatch Physical damage and weight-driven downcycling.

3.3 Academic Discourse in Peer-Reviewed Journals

Following the search strategy outlined in section 3.1, the selected peer-reviewed journals are analyzed and mapped into five categories. The conceptual positioning of these research focuses is illustrated in Figure 3-2.

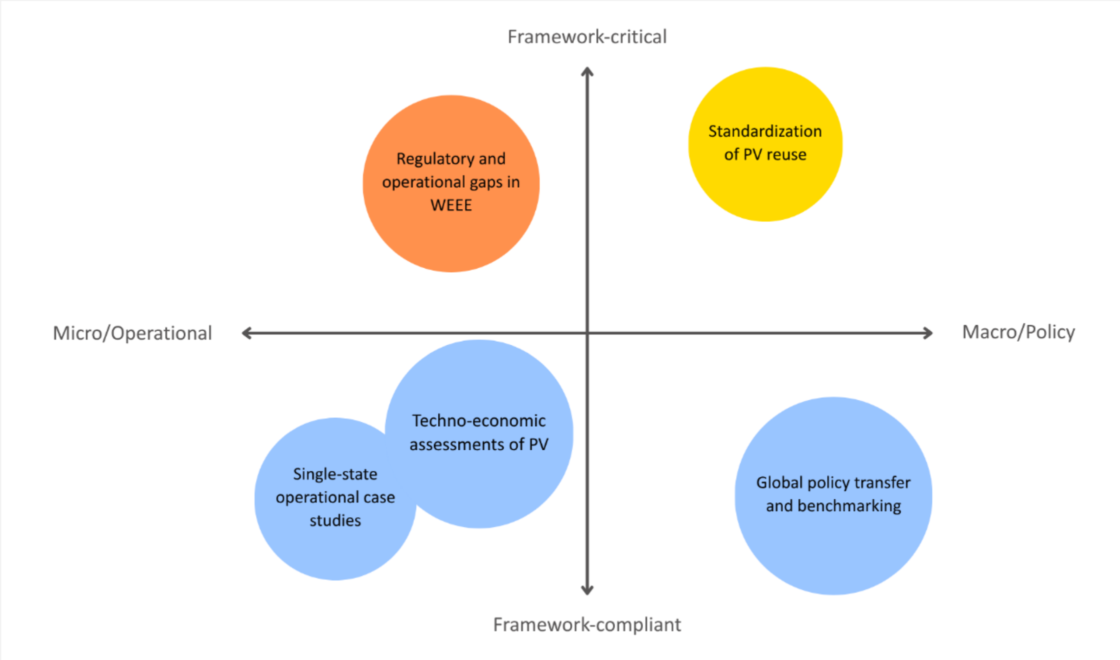

Figure 3-2. Academic Focus Areas in PV EoL Research

Global Policy Transfer and Benchmarking

Within the peer-reviewed literature selected for this thesis on PV EoL management and the WEEE Directive, the largest cluster of research focuses on global policy transfer and benchmarking. Many researchers see the EU legal framework and the EPR system as benchmarks. They refer to the European experience and explore how to transfer it to other countries with varying levels of solar industry development. The broad macro-level research covers major emerging and established markets worldwide including Australia, Japan, China, India, Brazil, Saudi Arabia etc.

A recent study on the Saudi Arabian solar market provides a clear example. It compares waste management laws across Germany, Japan and China in order to guide the creation of a future policy framework for Saudi Arabia. As Ali et al. (2024) point out, to address this challenge sustainably, it is essential for the country to learn from the established practices of developed nations like Germany. They emphasize the need to introduce and implement an EPR policy for managing future PV waste so that environmental protection and economic growth can both be secured.

While these cross-country studies largely enrich the global PV policy database, they share the same theoretical assumption. Most literature treats the existing EU waste framework as a default and valid baseline for policy transfer. However, the applicability is rarely questioned for PV EoL management, especially the challenges of using this framework to govern high-value, long-term energy assets. This outward promotion of policies may delay deeper academic discussions on the structural fit of the system itself.

Techno-Economic Assessments of PV Recycling

Another key research area focuses on techno-economic assessments of closed-loop material recovery. Scholars use cost-benefit models, net present value analysis and life cycle assessments (LCAs) to systematically compare the economic viability of mechanical, thermal and chemical recycling methods. A clear consensus runs through these studies. Downcycling that relies strictly on physical shredding to hit current weight-based recovery targets yields low direct economic returns and causes the irreversible loss of critical strategic materials such as silicon and silver (Ramirez-Cantero et al., 2026). At the same time, although they deliver substantial environmental benefits, high-value extraction technologies capable of true closed-loop recycling consume large amounts of energy and require costly chemical reagents. These advanced methods fail to reach financial breakeven under existing market dynamics and upfront recycling fee structures (Deng et al., 2019).

By applying advanced data models, several prominent studies pinpoint the major economic obstacles that prevent effective high-value recycling. For instance, D'Adamo et al. (2023) quantitatively assess the profitability of PV recycling plants. They found that closed-loop projects relying solely on secondary material sales are not viable without aggressive policy interventions. Their model specifies that a recycling facility only achieves a positive net present value when the government provides financial subsidies equivalent to an avoided landfill cost of 200 to 250 euros per tonne. A recent comprehensive techno-economic review outlines a similar dilemma. Advanced thermal recycling processes can successfully recover silicon at up to 99.9999% purity alongside silver recovery rates exceeding 90%. However, these processes usually operate at a temperature above 500°C. The high consumption of energy is the main shortcoming of such technologies (Tiwari et al., 2026). These studies deliver a clear consensus: the direct financial returns from extracting high-value metals currently fail to offset the severe operational costs of these complex processes.

From an academic perspective, these techno-economic assessments are highly valuable. They establish quantitative baselines for the commercial potential of different recycling methods and clarify the financial thresholds for the transition from laboratory experiments to industrial scale. However, this research area has its inherent flaws. The economic models rely heavily on idealized market assumptions and rarely factor in real-world complexities such as cross-border logistics costs, actual waste collection rates and a fluctuating policy environment. Despite the methodological limitations, the literature offers crucial empirical backing for this thesis. Since high-purity silicon and silver recovery has clear financial viability issues, proactive policy measures are essential. Future regulations must incentivize technological innovation and expand market scale to make high-value recycling for PV modules economically sustainable.

Single-state Operational Case Studies

This academic research explores how the WEEE Directive plays out by looking directly at the operational reality of PV EoL management within individual member states. These papers predict future waste surges in a given nation, evaluate the commercial potential of local recycling markets and measure the actual material recovery rates of existing national facilities. By looking at a single country, this perspective provides the most direct data on how EPR truly functions at the local level.

Using Austria as an example, Dobra et al. (2020) closely evaluate the waste management of PV modules and point out that although the country's PV waste volume is too small for dedicated facilities, an inevitable surge will soon force the country to build professional treatment systems that comply with EU standards. Shifting the focus to Southern Europe, Spain and Italy face exponential waste growth. This surge puts heavy compliance pressure on local governments and at the same time, it creates real economic opportunities for both nations to develop localized circular economy infrastructure (Oñate et al., 2024). Umar et al. (2025) evaluate the operational efficiency of EPR models within individual borders and argue that enforcement strength is the decisive factor for the sustainable operation of local recycling projects. Here, enforcement strength extends beyond the existence of statutory requirements to include the regulatory capacity of local authorities to monitor waste flows and penalize non-compliance. According to this article, even with the unified management framework such as WEEE, significant variations in recycling rates occur due to differences in institutional oversight and the ability to curb illegal dumping. It also stresses that in many regions, the absence of robust auditing mechanisms allows retired modules to leak into informal markets, thereby depriving formal recycling facilities of the consistent waste streams needed to achieve economies of scale.

The core value of this academic focus lies in its highly practical nature. By looking at just one country, researchers can gather information such as local transport networks, market size and the execution of the law. This ground-level view helps local officials and businesses plan their investments accurately. Due to its narrow focus and geographical constraints, this perspective however cannot systematically evaluate the overall effectiveness of the WEEE Directive in governing PV waste.

Regulatory and Operational Gaps in the WEEE Framework

There have been ongoing academic discussions regarding the flaws of the EU WEEE Directive in managing PV waste. Yet, the current research landscape remains highly fragmented. The most intensely debated focus is on the weight-based recycling metrics. Researchers point out that measuring success purely by weight inherently sustains downcycling practices and fails to promote the recovery of critical and valuable materials such as high-purity silicon (Stokvisch, 2022). Another critique is that treating bulky solar panels like ordinary household appliances creates immense pressure on existing local logistics networks. The absence of detailed operational guidelines has also been discussed recently. Scholars argue that the Directive fails to offer unified rules for proper collecting and sorting. By leaving these critical implementation decisions entirely to the discretion of individual member states, the framework leads to misaligned incentives, weak coordination and underdeveloped governance structures across the EU (de Moor, 2025).

A closer look at specific journal articles offers a clear view of these scattered frictions. For weight metrics, Kastanaki and Giannis (2022) point out that the regulatory focuses on pure volume forces recycling facilities to rely on basic downcycling. To meet legal targets at the lowest cost, recyclers often just crush the panels mechanically. This allows them to easily extract heavy but low-value materials like glass and aluminum frames. However, this crude approach destroys the trace amounts of valuable and strategic metals in the modules, causing the permanent loss of high-purity silicon and silver. Logistics and sorting present another hurdle. Mahmoudi et al. (2019) stress that treating PV modules as standard household electronic waste significantly underestimates the operational complexity. Solar panels are large in size, heavy and fragile. The removal and transport over long distances require strict safety protocols and specialized heavy machinery. Massive glass shattering and potential heavy metal leaks may happen during operation without precaution. Without separate management, local municipalities must shoulder immense administrative and logistical responsibilities. Beyond physical operations, Yavuz et al. (2025) critique the lack of specificity in the Directive. They point out that the WEEE Directive and its annexes provide no specific operational standards for separating and disposing of PV components. Instead, the framework pushes all implementation details onto individual member states. This excessive legislative decentralization creates highly inconsistent compliance standards and recycling thresholds across the EU. It severely cripples the economies of scale needed for advanced transnational recycling facilities. Furthermore, this patchwork of local regulations brings huge administrative compliance burdens for producers operating across multiple borders.

This academic focus successfully pinpoints where a macro-level policy fails on the ground. Specifically, it highlights the invisible loss of valuable materials due to the weight-based metrics and the daily struggles of local operators. These practical insights provide policymakers approaches in improving current producer responsibility programs. However, the literature remains highly scattered in pointing out the limitations of the WEEE Directive in managing EoL of PV modules. Most studies focus on only one issue at a time, such as the negative impacts of weight-based rules. These isolated failures can be woven into a unified framework in order to explain the deeper logical connections linking the everyday frictions and inspire better-informed solutions.

Standardization of PV Reuse

Current academic discourse on PV reuse is relatively sparse. Existing literature mainly focuses on the business potential within a circular economy, EPR in international second-hand markets and the need for a unified technical certification. Scholars are beginning to see the reuse of PV modules as a key driver for sustainable development in the energy sector.

Developing circular economy solutions for PV modules is not merely done for the purposes of environmental compliance, but represents an economic opportunity. The potential lies not only in the direct resale profits of second-hand panels in emerging markets. It also boosts the development of a new service industry dedicated to panel testing and refurbishment, effectively reducing producers' dependence on expensive virgin materials. However, the lack of standardized component design and absence of material data makes repair and reuse difficult to implement (Chhillar et al., 2025). Cimadomo (2024) explores the practicalities of exporting used panels from the EU to other emerging countries and analyzes how proposed international EPR frameworks can systematically regulate these cross-border transactions in the future. The performance evaluation of second-hand modules is key to scale up the reuse market. Without globally recognized testing protocols and quality rating standards, buyers and financial institutions struggle to accurately assess the remaining lifespan of used assets. The establishment of a unified technical baseline and certification is essential to unlock the potential of the second-hand PV market (Basnet et al., 2025).

Although current academic discussions on PV reuse are somewhat limited, the practice shows great potential to reshape the entire value chain of PV EoL management. The question remains whether the current WEEE framework actually facilitates or inhibits the development of PV reuse. Examining this specific literature provides a vital entry point for the subsequent discussion on the structural mismatch of the WEEE Directive in managing long-lasting PV infrastructure.

3.4 Operational Realities in Industry and Agency Reports

Given that PV EoL management relies heavily on local policy implementation and industrial practice, industry reports and official publications provide a crucial empirical foundation for understanding current execution realities. This section systematically reviews approximately 18 key grey literature documents, including publications from the JRC, IEA PVPS, IRENA and various national PROs. Three main areas of consensus have emerged across the industry and regulatory landscape.

First, at a macro-strategic level, leading institutions warn that the current installations boom will inevitably evolve into a future PV waste tsunami, as illustrated in Chapter 1. They also position PV technology as critical strategic infrastructure essential for the EU's energy independence. According to a report from JRC (2026), rooftop solar systems in Europe could potentially meet nearly 40% of the EU's long-term electricity demand. This massive infrastructural scale fundamentally distinguishes PV modules from traditional household appliances. Recent industry assessments directly categorize decommissioned panels as urban mines rich in critical strategic resources like silicon, silver and copper. Establishing an efficient EoL value recovery loop allows Europe to effectively hedge against external supply chain disruptions. It also provides the secondary materials needed for the revitalization of PV manufacturing within EU (IEA PVPS, 2025b; SolarPower Europe, 2025). This top-level industry consensus invites reflection on the applicability challenges that the WEEE Directive faces in managing the EoL of long-lasting energy infrastructure such as PV modules.

Second, on a micro-operational level, national reports from PROs reveal widespread logistical and compliance difficulties caused by forcing large and fragile solar panels into existing municipal recycling networks. PV modules significantly exceed standard electronic waste in both size and weight. Mixing them with traditional household appliances for transport and rough handling frequently leads to massive glass breakage. This physical damage directly blocks the possibility of high-value material extraction (El-Kretsen, 2025; Soren, 2025b). Besides this, industry surveys on specific national compliance expose overwhelming administrative friction. PV producers selling to multiple European countries face disproportionate management costs when fulfilling their responsibility due to fragmented registration mechanisms and fee structures across member states (IEA PVPS, 2024a). The statistics and operational insights from these PRO reports directly inform the quantitative analysis in Chapter 5 and build the empirical pillar for the thesis in demonstrating the structural failure of the WEEE framework in managing PV EoL.

Third, regarding high-value recovery, industry assessments suggest that the weight-based compliance metrics of the WEEE Directive in fact penalize module reuse and force the downcycling of critical materials. In the WEEE framework, preparing for reuse and recycling is merged into a single weight-based target. This setup creates a strong perverse incentive. Faced with high labor costs and strict compliance requirements to test and prepare second-hand panels for the market, operators prefer cheap mechanical shredding to rapidly hit the tonnage target. This economic reality completely undermines the viability of reuse (Soren, 2025b). At the same time, this aggressive shredding approach leads to material value loss. Recyclers could reach the 80% weight threshold by separating the heavy glass and large aluminum frames. However, this crude process permanently contaminates trace amounts of high-purity silicon and silver. These valuable raw materials then are downcycled into low-grade construction materials or lost in smelting (IEA PVPS, 2025a).

3.5 Research Gap: A Systemic Perspective on Structural Mismatch

Although academic discourse on the WEEE Directive and PV EoL management is expanding, existing literature lacks a systemic perspective that bridges theoretical policy design with on-the-ground operational realities. A large amount of literature sees EPR and the WEEE Directive as a default baseline for global policy transfer without critical examination of its suitability for solar assets. Regarding the fragmented regulatory frictions identified, scholars usually propose isolated operational patches rather than confronting the fundamental institutional failures. Moreover, existing techno-economic models are somewhat idealized and fail to consider the compliance dilemmas faced daily by the operators.

Few studies investigate the root cause for these scattered operational frictions: the inherent structural mismatch between a regulatory framework designed for short-lived consumer electronics and the physical, financial and strategic realities of long-lasting energy infrastructure. This thesis aims to address this research gap. By synthesizing fragmented academic insights and operational evidence, it identifies the structural mismatch and provides the necessary theoretical and empirical direction for comprehensive policy reform.

4 Methodology

4.1 Research Design: Sequential Explanatory Mixed Methods

This thesis employs a sequential explanatory mixed method approach to evaluate complex governance challenges. The primary purpose of this methodology is to use qualitative results to assist in explaining and interpreting the empirical findings generated by a primarily quantitative design (Creswell & Poth, 2018). Guided by this design framework, the research is structured into three interlocking phases, providing a systematic approach to investigating the structural mismatch of the WEEE Directive in managing PV EoL. As illustrated in Figure 4-1, the process begins with a Foundation Phase, followed by two primary stages of quantitative and qualitative analyses.

The Foundation Phase serves as the analytical starting point of the thesis, focused on establishing a comprehensive knowledge base through systematic review of legislative frameworks, peer-reviewed literature and industry reports. By synthesizing these diverse sources, insights are gathered to provide the necessary theoretical and contextual grounding for the subsequent analyses.

Phase 1 involves the identification and quantification of the structural mismatch through the analysis of quantitative data. During this phase, secondary data such as collection rates, fee levels and material recovery performance are analyzed to establish the regulatory misalignments within the selected EU Member States. This empirical foundation provides the necessary evidence to identify specific anomalies and trends that require further investigation.

Phase 2 consists of a qualitative investigation into the underlying institutional factors that sustain these misalignments. By conducting semi-structured interviews with key stakeholders, this phase seeks to uncover the institutional path dependence and administrative barriers that macro-level statistics cannot reveal. These two phases complement each other and ensure that the statistical findings are not analyzed in isolation but are grounded in the operational reality.

To ensure the analytical depth of both phases, the thesis utilizes France, Germany and Sweden as representative national examples. These three countries act as the empirical anchor for the entire thesis. They provide the secondary data used for quantitative benchmarking in phase one and represent the diverse regulatory environments explored through expert testimony in phase two. By focusing on these specific markets, the research facilitates a grounded evaluation of how the WEEE Directive is implemented within the PV sector across representative European markets.

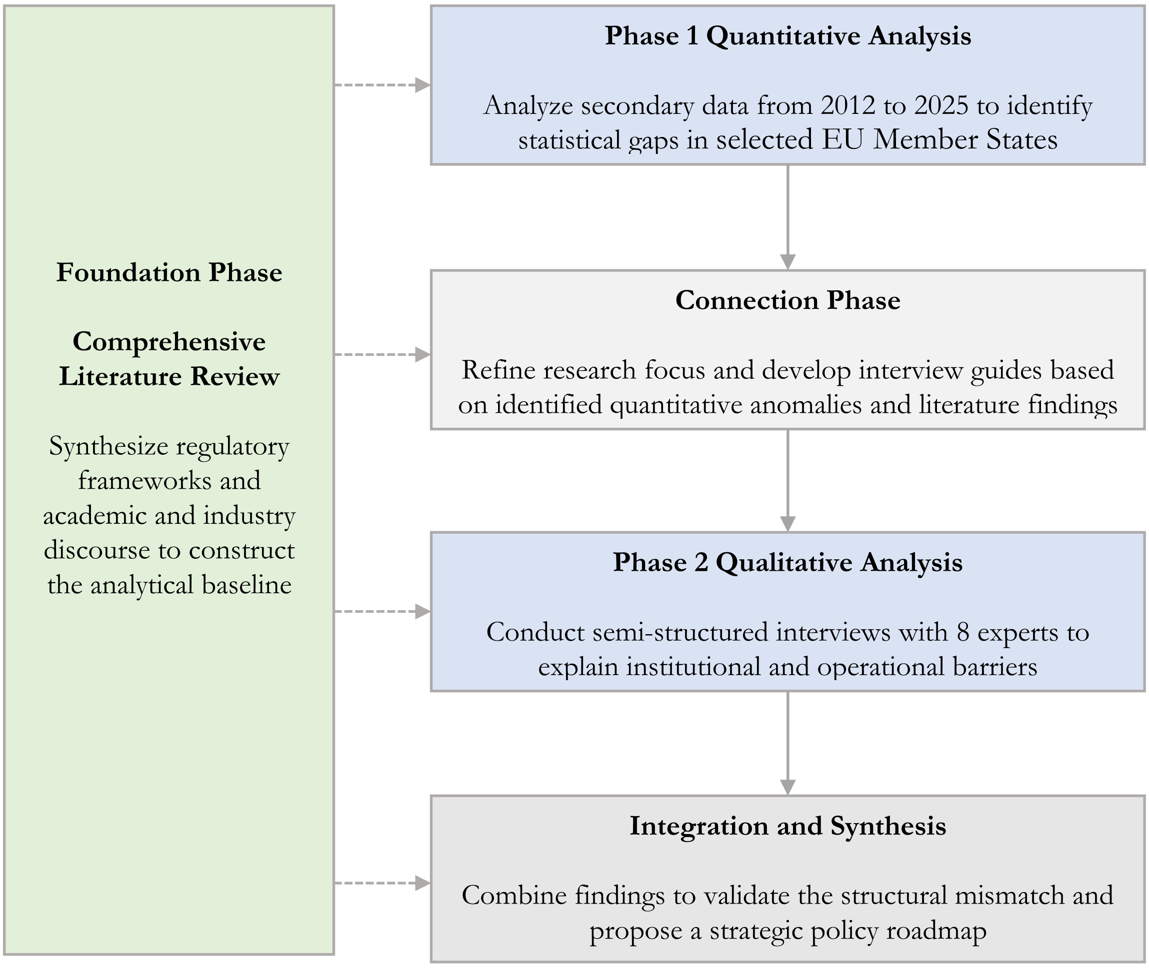

Figure 4-1. Sequential Explanatory Mixed Methods Research Design

4.2 Quantitative Data Collection

The quantitative analysis employes a comprehensive range of secondary data sources from official international and national sources to ensure empirical validity. The research is primarily anchored in two data streams: the Eurostat database provides macro level metrics for the EU regarding electronic waste categories (Eurostat, 2024) and the national annual reports from specific producer responsibility organizations which include Soren in France, Stiftung EAR in Germany and El-Kretsen in Sweden facilitates an in depth study of the various dimensions of structural mismatch. To bridge potential statistical gaps and ensure a continuous timeline, these primary sources are supplemented by global benchmarks from the International Energy Agency (IEA PVPS, 2025a), renewable energy assessments from the International Renewable Energy Agency (IRENA & IEA-PVPS, 2016) and market insights from SolarPower Europe (SolarPower Europe, 2025). Relevant peer-reviewed academic journals also provide information concerning the economic value of recovered materials and fill specific data voids. This multi-layered data collection strategy builds a solid evidence foundation for evaluating the operational performance of PV EoL management across the EU markets.

To identify and validate the structural mismatch, the thesis prioritizes specific indicators categorized in three dimensions: temporal-financial dynamics, logistical operations and material recovery performance. The first dimension scrutinizes the fundamental tension between the long operational lifespan of PV modules and the short-term annual compliance cycles mandated by the current regulation. This analysis quantifies whether existing recovery fees and financial guarantee funds are sufficient to meet future decommissioning liabilities, taking into consideration of the big time lag between market placement and waste generation (SolarPower Europe, 2025). The second dimension puts a focus on logistical operations, examining parameters such as the technical and financial requirements of dismantling, transportation distance and storage infrastructure. The third dimension evaluates the efficiency and economic viability of material recycling and recovery. The selection of these indicators is informed by the availability of current data, recognizing that while some statistics remain aggregated within broader categories, specialized organizations such as Soren (2023) offer the granular details necessary for this analysis.

Data collection is primarily concentrated within the geographical and time scope defined in the preceding chapter of this thesis. Data cleaning and pre-processing such as the standardization of various reporting units into metric tonnes to ensure comparability is carried out. In instances where official national records present statistical gaps or data fragmentation, the study shall interpolate the missing data points and cross-reference with supplementary reports. This preparation phase ensures that the datasets used are suitable for the subsequent analysis of system performance.

4.3 Qualitative Interview Design

Semi-structured interviews are conducted at the qualitative analysis phase to explore the institutional and operational drivers behind the misalignments identified in the quantitative phase. By engaging directly with key stakeholders, the thesis aims to explore further how path-dependence and policy design influence the PV EoL management practice.

The qualitative research involved sending over twenty interview requests to professionals across the solar energy and waste management sectors. Out of these, eight experts agreed to participate. The participants are classified into three categories to capture a holistic view of the problem discussed in the thesis. The first category includes representatives from legislative bodies, environmental regulatory authorities or independent academic researchers specializing in WEEE policy formulation and governance. They provide insights on the overarching regulatory architecture, evaluating the efficacy of the current legal framework and identifying structural limitations within its practical implementation. The second category focuses on compliance and operational management, comprising professionals from PROs and individual recycling service providers who are responsible for the on-the-ground implementation of the legal framework through actual financial, logistical and value recovery operations. The third category represents industry practitioners, specifically PV manufacturers and producers who initiate market placement and bear the compliance obligations mandated by the WEEE Directive. Geographically, most of the interviewed experts are based within the European Union. However, the group also includes participants located in other regions who possess extensive experience in both European and international markets.

The design of interview questions directly translates the regulatory and operational challenges discussed in previous chapters into practical inquires. The structure of the interview protocol strictly follows the core mismatches identified in the literature review. This approach ensures that the primary data collection actively validates the academic discourse. The questions fall into four primary thematic categories: Financial sustainability, logistical efficiency, value recovery and regulatory reform. To clarify this design process, below Table 4-1 maps the direct relationship between the identified structural misalignments and the specific questions posed to the stakeholders.

Table 4-1. Operationalization Matrix of the Interview Protocol

Themes	Key policy and operational concepts	Corresponding interview questions (Appendix)
Financial viability	Pay-as-you-go risks, long-term guarantee mechanism, future waste surge financing	Q3: Evaluation of WEEE financial options and PRO fee adequacy
Logistical Efficiency	Bulky infrastructure handling, dispersed installations, collection damage	Q4: Logistical comparisons between heavy PV modules and standard e-waste Q12: Physical damage to panels during municipal collection
Strategic value recovery	Weight-based targets, downcycling, critical material extraction, waste hierarchy	Q5: Operational reality of the 80% weight target Q6 & Q7: Technical and economic barriers to the waste hierarchy and trace material recovery Q13: Economic viability of specialized recovery technology
Policy & institutional reform	National transposition variations, eco-design, institutional barriers, dedicated PV regulation	Q8, Q16 & Q17: Ideal EoL management models and the validity of a dedicated PV EoL regulation Q11: Political and institutional barriers to legislative revision Q15: Feasibility of eco-design and built-in reuse potential Q9, Q10 &Q14: Impacts of national transpositions, Member State flexibility and B2B/B2C compliance costs

The interviews were conducted online and typically lasted between 45 to 60 minutes. The semi-structured format allowed for a flexible yet rigorous inquiry. All interviews were recorded and transcribed with explicit permission, and the identities of the experts are fully anonymized to encourage candid discussions regarding policy failures and economic barriers. This qualitative evidence was then synthesized with the quantitative findings to provide a coherent explanation of the current systemic mismatches in the photovoltaic waste regime.

Table 4-2. Overview of Interviewed Experts

Participant Code	Stakeholder Category	Professional Role	Years of Expertise
E1	Policy/Research	Senior Consultant in Climate Policy & Circular Economy	10+
E2	Policy/Research	Senior Researcher in PV Reliability & Performance Modeling	10+
E3	Policy/Research	Sustainability Manager & Circular Economy Researcher	6
E4	Policy/Research	Academic Researcher in PV Circular Business Models	5
E5	PRO/Individual recycler	Head of EoL Operations & Electronics Reuse	8+
E6	PRO/Individual recycler	CEO of a National Regulatory Clearing House	23
E7	Industry practitioner	Chief Procurement Officer for a Utility-Scale IPP	16
E8	Industry practitioner	Strategic Advisor in Renewable Energy Sustainability	10+

4.4 Country-Specific Examples

Within the sequential explanatory framework, this thesis utilizes examples from selected member states to maintain a critical balance between analytical depth and regional representativeness. While the WEEE Directive establishes a unified regulatory framework at the European level, its actual execution heavily relies on national transpositions. Examining a single market would obscure the crucial distinction between local administrative failures and systemic flaws, whereas analyzing all member states risks yielding superficial generalization of results. Therefore, to ensure empirical depth, this thesis evaluates the performance of three representative member states: France, Germany and Sweden.

The selection of these three nations is driven by their active involvement in PV deployment and their distinct regulatory approaches in translating the WEEE Directive into national practice.

France operates a uniquely specialized governance structure characterized by a mandatory PRO. The French regulatory framework legally compels all PV producers to participate in a centralized compliance scheme managed by Soren, creating a highly organized ecosystem for EoL management (Mahmoudi et al., 2021). From a data collection perspective, the presence of a dedicated organization is invaluable. It yields the highly granular operational statistics needed to establish a quantitative benchmark for targeted logistical and material recovery strategies. France is also a highly mature PV market with over 22 GW of cumulative installed capacity achieved by the end of 2024 (SolarPower Europe, 2025). This market maturity, combined with its strict governance structure, makes France an exemplary case for evaluating how a top-tier European market manages the escalating operational demand of decommissioning projects.

Building upon the regulatory landscape outlined in Chapter 2, Germany is selected because it is a European solar pioneer and an example of decentralized waste governance. Historically, Germany represents the largest and most mature PV market in the EU, holding the highest cumulative installed capacity (Babaei & Nasr Esfahani, 2024). This market maturity is methodologically crucial as its vast installation base provides the quantitative data required to analyze the decommissioning of legacy assets and early-stage financial reserve vulnerabilities (Sharma et al., 2019). Furthermore, the German transposition of the WEEE Directive relies on a highly competitive compliance ecosystem coordinated by a central administrative clearing house, known as Stiftung EAR (Diedler et al., 2018). Selecting this specific regulatory architecture allows the research to evaluate how extended producer responsibility functions without a single monopolistic entity, offering a critical structural contrast to the French governance system.

The methodological selection of Sweden is driven by the unique geographical variables it introduces. Sweden has a low population density and highly decentralized PV installations across vast distances. It represents the logistical extreme of the European market. This spatial distribution is empirically documented as being driven by local municipal actors and small-scale prosumers rather than centralized utility plants, creating a fragmented asset map (Palm, 2016). Such fragmentation provides essential data to test the economic viability of the overarching regulatory framework when transportation costs become the primary operational barrier. Operational reports from the national compliance scheme confirm that maintaining a collection network across these vast distances incurs disproportionately high logistical expenditures compared to densely populated European regions (El-Kretsen, 2024a). In addition, its dependence on established municipal collection networks, rather than specialized producer schemes, provides a crucial structural contrast. By analyzing this decentralized operational environment, the research isolates whether material recovery inefficiencies are caused by localized geographical challenges or by inherent structural flaws within the directive itself.

Table 4-3. Rationale for Country-selection

Country	Market	Regulatory	Methodological Value
France	Mature top-tier market	Centralized mandatory PRO managed by Soren	Benchmarks logistical efficiency and material recovery using granular operational data
Germany	Solar pioneer with the highest installed capacity	Decentralized competitive ecosystem via a central cleaning house	Quantifies early-stage financial vulnerabilities and legacy asset decommissioning
Sweden	Logistical extreme driven by small-scale prosumers	Dependence on established local municipal collection networks	Isolates spatial logistical challenges from systemic regulatory flaws

5 Documentary Evidence of the Structural Mismatch

5.1 Mapping the Structural Mismatch

This chapter utilizes industry report and market data to systematically validate the fundamental inadequacies of the current EU WEEE Directive in governing the EoL management of PV modules. As illustrated previously, the WEEE regulatory framework was specifically designed to manage short-lived consumer electronics with fast turnover rates. PV modules, on the contrary, function as durable energy infrastructure. The physical characters and economic realities are completely different from those of standard household appliances. Putting these long-term assets into a conventional electronic waste regime has consequently triggered a severe structural mismatch. The persistent operational frictions emerging in practices serve simultaneously as the inevitable consequence of this policy misalignment and the definitive empirical evidence validating the systemic failure of the framework.

To objectively demonstrate the widespread and systemic nature of this mismatch, the following analysis uses quantitative data and operational reports from France, Germany and Sweden. These three nations are not selected to conduct a comparative analysis. Rather, they represent distinct regulatory ecosystems encompassing centralized, decentralized and semi-centralized governance models. By evaluating the empirical outcomes across these varied frameworks, this chapter arrives at a core argument. The inherent structural flaws of the WEEE framework inevitably manifest in real-life operations regardless of how individual member states transpose the Directive at the national level.

Building on the literature review, the structural mismatch manifests across three core dimensions, namely financial mechanism, logistical operations and high-value recovery. Table 5-1 provides a comprehensive overview of the incompatibilities across these areas and highlights the systemic consequences they trigger in practice. It serves as an analytical map for the data validation presented in the subsequent sections.

Table 5-1. Manifestations of the Structural Mismatch Across Key Dimensions

Dimension	WEEE Framework (Consumer Electronics)	PV Infrastructure Reality	Structural Consequences
Financial	**Brief lifespan and immediate funding.** The system operates on a fast financial loop. Fees collected at market entry are immediately deployed to treat current waste. Because consumer electronics have a brief lifespan, the products reach their disposal stage quickly and the entire financial cycle closes without requiring long-term capital retention by the PRO.	**Extended lifespan.** Modules operate for 25 to 30 years. This creates a massive time lag between installation and decommissioning.	**Funding deficits and capital lock-in.** ● Prolonged capital freeze ● Financial deficits facing future inflation ● Widespread orphan waste from online free riders ● B2B orphan waste from corporate bankruptcies
Logistical	**Municipal network integration.** The framework was originally designed to utilize existing municipal collection points for moderately sized household waste.	**Dispersed distribution and physical fragility.** PV systems are highly decentralized. PV panels are bulky, heavy and fragile.	**High logistic costs and physical damage.** ● High dismantling thresholds and EPR funding exclusions block collection at the source ● Geographic dispersion and massive volume drive reverse logistics costs to unsustainable levels

			● Municipal collection stations lack the physical capacity for bulky panel influxes ● Long-distance transportation shatters fragile panels and eliminates high-value recycling potential
Value	**Weight-based volume targets.** The framework relies on mass-based recovery and recycling quotas to rapidly reduce the physical volume of waste entering landfills.	**Reuse potential and precious trace metals.** The core economic and strategic value lies in trace amounts of high-purity silicon and silver. Intact secondhand panels also possess significant market reuse value.	**Forced downcycling and high-value and critical material loss.** ● Minimal reuse market ● Costly trace silver and silicon extraction ● Irreversible downcycling through crude shredding

5.2 The Financial Mismatch

The main reason for the financial mismatch in PV EoL management lies in an inherent time-lag contradiction between the immediate funding requirements of existing financial guarantee mechanisms and the exceptionally long lifespan of PV modules. Under the WEEE Directive, producers are legally obligated to provide insolvency-proof financial guarantees via blocked bank accounts or recycling insurance the moment their products enter the EU market. As a result, large amounts of capital are locked away or critical bank credit lines are continuously occupied throughout the entire service life of the panels (Lighthief International, 2026). From the perspective of corporate finance, this requirement severely increases the opportunity cost of capital. Money that could otherwise fund technological innovation or operational expansion is frozen, thereby depriving companies of their ability to leverage these funds for potential profit generation.

Take Germany as an example. Through the national registry Stiftung EAR, PV producers must submit annually updated insolvency guarantees for their B2C sales. According to the 2025 updated metrics, the required financial guarantee is calculated by multiplying four parameters. The formula is Guarantee Amount = Annual Registration Base Quantity × Anticipated Return Rate × Anticipated Disposal Costs × Anticipated Average Lifespan (Stiftung EAR, 2024).

Consider a medium-sized enterprise introducing 50,000 standard solar panels to the German market in a given year. Assuming an average weight of 20 kilograms per panel, the annual placement totals 1,000 tonnes. Using the calculation tool provided by Elektro Garantie, a collective manufacturer scheme for B2C electronic devices, the required insolvency-proof guarantee amount for 1,000 tonnes of PV panels is €36,000. If the company chooses to deposit this capital directly, maintaining an annual placement of 1,000 tonnes over the 20-year statutory lifespan would escalate the cumulative guarantee to €720,000. This massive sum would remain strictly frozen in bank accounts and entirely inaccessible for operational use. Companies typically avoid locking such substantial capital in bank accounts and instead opt for insurance. According to the calculation from this scheme, the annual insurance premium combined with service fees amounts to €4,284.95. This figure seems to be manageable. However, the company needs to pay insurance for this quantity every year until the end of its 20-year anticipated average lifespan. If the company continues to place 1,000 tonnes of panels on the market annually, the insurance amount compounds exponentially. By the tenth year, the company will face a pure annual cash outflow of €39,699.50. Over a ten-year period, the cumulative cost for this compliance will reach €219,922.25 (EPR-System GmbH, 2026).

Based on solar module price assessments for early 2026, the wholesale market value for mainstream PV panels in Europe remains constrained at approximately €0.11 per watt (pv magazine, 2026). For a standard 450W module, this equates to a unit price of €50. A medium-sized enterprise distributing 50,000 such modules annually would therefore generate a total gross revenue around €2.5 million (pv magazine, 2026). With this high-volume and low-margin business model, net profit margins are frequently compressed into the low single digits. Even with an optimistic net profit of €100,000, the financial burden of environmental compliance is disproportionately high. Even if a company opts for the collective insurance scheme to avoid the massive capital freeze, the compounding insurance premiums become a financial burden. What's more, the insurance is only a safeguard for bankruptcy. Producers remain entirely responsible for financing the actual take-back of decommissioned panels including the logistics and recovery.

Another scenario is that manufacturers entrust these prepaid funds to PROs for collective management. The accumulated capital may struggle to withstand the external economic volatility over the coming decades. Sustained inflation and the increasing costs of logistics and labor will likely render current fees insufficient for actual future treatment expenses. Research indicates that recycling funds gathered early under static parameters, which fix contribution rates based entirely on present economic conditions without dynamic adjustments, face severe depreciation by the end of a panel's 20 to 30 years' lifecycle. They will ultimately fail to cover the physical disposal costs actually incurred, leaving an unbridgeable financial deficit within the waste management system (IRENA & IEA-PVPS, 2016).

The French PRO Soren serves as an illustrative example. It charges PV producers a visible eco-contribution that functions as a fixed upfront environmental fee. Based on the regulatory framework outlined by the French Agency for Ecological Transition (ADEME, n.d.), this unit environmental fee operates on a strict pay-as-you-go financing model. The calculation logic can be mathematically expressed as follows:

$$Unit\ Eco - contribution = \frac{Total\ Processing\ Costs + Operational\ Expenses}{Total\ New\ Panels\ Placed\ on\ Market}$$

The number of new panels entering the EU market is massive, while the volume of currently decommissioned panels remains relatively small. This creates a massive denominator against a minimal numerator, driving the unit eco-contribution fee down to a mere €0.69 (Soren, 2024b). Assuming a standard module weight of 20kg, the total eco-contribution for one tonne of PV panels amounts to only €34.50. This upfront fee falls drastically short when compared to the true financial liability incurred at the end of the panels' lifecycle. According to recent field data from the EU PV recycling market, the recycling and logistics costs range from €150 to €300 per tonne in Southern Europe. Meanwhile, regions with stricter environmental standards like Germany face costs up to €400 per tonne (Euro-Inox, 2025). Adopting a conservative baseline cost of €150 and introducing a modest 2% annual inflation rate over the 25-year lifespan of a module, the future treatment cost per tonne is:

$$C_{future} = 150 \times (1.02)25 \approx €246.09/\text{tonne}$$

The €34.50 collected today represents a mere fraction of the projected €246.09 required to process that same tons of waste in the future. This static eco-contribution fee merely covers current operational expenses. It fails to lock in sufficient capital for future inflation and the impending wave of EoL processing.

Admittedly, the environmental fee will inevitably rise as future installations peak and the volume of retired panels surges. However, by the end of the 25-year lifespan of these panels, the majority of the manufacturers active today may have gone bankrupt or exited the market. This creates a large amount of unaccounted orphan waste. Under this pay-as-you-go system, future PV producers and consumers are forced to shoulder these historical treatment bills (Buehler, 2019b). This cross-generational subsidization is highly unfair and fundamentally violates the core polluter-pays principle of the EPR framework. Simply put, the pay-as-you-go mechanism relies heavily on current cash flow and is unsuitable for PV modules due to their exceptionally long lifespans.

Beyond the financial erosion caused by extended time horizons, another major reason for the financial mismatch is the high probability of orphan waste emerging due to regulatory loopholes. In the B2C sector, numerous cross-border e-commerce platforms and online sellers freeride. A dedicated study from the German Environment Agency points out a critical regulatory blind spot. Without a physical corporate presence within the EU, numerous cross-border online sellers from third countries systematically evade their legal registration and financial pre-payment obligations under the WEEE Directive (Hermann & Schomerus, 2020) . These online sellers strip PV products of their mandatory financial guarantees at the source by bypassing both registration and active participation in PROs. Online free-riding accounts for an estimated 5%-10% of total market sales (WEEE Forum, 2019). For the PV industry with very high compliance costs, such free-riding not only transforms millions of incoming solar panels into future orphan waste, but also ultimately puts a massive financial burden of EoL disposal onto compliant companies and municipal management systems.

In the B2B sector, the WEEE Directve grants corporate entities substantial financial negotiation space and lenient management. Article 13 specifies that B2B producers are allowed to conclude agreements stipulating other financing methods (European Parliament and Council of the European Union, 2012). This becomes problematic given the massive installation volumes typical of B2B PV projects. The EU added about 6.5 gigawatts of new PV capacity in 2024. Within this massive volume, the market share of residential rooftop was 20%, commercial and industrial rooftop accounts for 39% and the biggest share is the utility-scale solar sector, which captures 42% of the market (SolarPower Europe, 2024). This means in the single year of 2024, an overwhelming 81% of all new PV deployment in the EU falls under the lenient financial frameworks of B2B agreements. The corporate lifespans of solar manufacturers frequently fall short of the physical longevity of the panels themselves. When these original installers or project developers go bankrupt or enter liquidation, the initial financial allocation agreements are rendered entirely obsolete. The massive B2B volume of panels will become orphan waste and the disposal costs again fall onto either landowners or local municipal finances (IRENA & IEA-PVPS, 2016).

5.3 The Logistical Mismatch

At the operational level, current regulations suffer from a severe logistical mismatch. First, the high professional threshold for dismantling and its exclusion from EPR funding inhibits the physical handover between consumers and collection networks. Second, the highly dispersed geographical locations of the installed PV modules with massive physical volume, drive reverse logistics costs to a significantly high level. Lastly, fragile glass panels are highly susceptible to mechanical shattering during long-distance transportation. This physical damage directly eliminates the potential for product reuse and the recycling of high-value materials.

For household electronic waste, consumers can simply unplug the device and return it free of charge to municipal collection points. PV panels, however, are heavy industrial electrical equipment deeply embedded in building roof structures or connected to high-voltage grids. It has been highlighted that the physical removal of these panels involves extreme electrical safety risks and requires professional engineering skills. Panels on residential rooftops often require dismantling by B2B networks, such as the installers who also take care of the dismantle and disposal. Ordinary end users are incapable of executing this physical detachment process by themselves (IRENA & IEA-PVPS, 2016). This dismantling threshold directly exposes a blind spot in the current regulatory design for reverse logistics. Under the existing EPR framework, the PRO financial pool only covers transportation and recycling costs incurred after the equipment reaches a designated collection point. The high dismantling expenses including the use of specialized heavy lifting machinery, scaffolding for roof access and expensive certified labor required to safely disconnect high-voltage electrical components are excluded from the fees paid to PRO and passed on to the solar system users.

Taking the operational reality of the El-Kretsen in Sweden as an example, the prepaid recycling fees (återvinningsavgift) do support logistics fleets in conducting on-site collections at designated commercial locations. However, according to the official operational guidelines of the recycling organization, decommissioned PV panels must be safely dismantled and packed onto standard pallets awaiting shipment (El-Kretsen, 2024b). This means the physical detachment of panels from rooftops or high-voltage mounts and the transfer to ground-level pallets falls completely outside the producers' responsibility. Without financial backing, the dismantling fees exceed the residual value of the panels, and end users are highly likely to abandon the decommissioned modules permanently.

Ordinary consumer electronic waste is typically concentrated in densely populated urban areas where it is collected and processed in bulk by municipal networks. Residential PV systems, however, present an extremely decentralized geographical footprint. Taking Sweden as an example, official statistics from the Swedish Energy Agency report over 250,000 grid-connected solar facilities nationwide, the absolute majority of which are small-scale residential installations. These panels are thinly scattered across independent rooftops in all 290 municipalities (Energimyndigheten, 2024). This creates an elongated geographical span, stretching from Skåne in the south all the way to Norrbotten north of the Arctic Circle.

In contrast to the highly dispersed installations, Sweden's major electronic recycling facilities are rather concentrated in the central and southern regions. For instance, the NG Metall facility, a major national processor for electronic waste, operates from its base in central Katrineholm (NG Metall, 2024). Stena Nordic Recycling Center, featuring advanced material separation capabilities, is located on the southwest coast in Halmstad (Stena Recycling, 2023). This geographical discrepancy forces decommissioned panels from northern or remote municipalities to travel extreme logistics routes, often spanning hundreds or thousands of kilometers.

Beyond decentralized locations and long transportation distances, the massive, heavy and fragile features of PV panels create further logistical barriers. A typical commercial module used for residential rooftops is about 2.3 square meters in surface area with a weight of around 24 kilograms per unit (Sykes, 2024). The combination of extended transportation distances and volume constraints drives an exponential increase in logistics costs. Quantitative research based on the US solar market reveals a critical financial bottleneck. Physical transportation alone costs 3.3 dollars per square meter, accounting for almost 50% of the total disposal expense (Markert et al., 2020).

The glass panels are highly susceptible to mechanical shattering during long-distance transport. Once broken, panels permanently lose the physical integrity for the secondhand market. The shattered glass also contaminates the valuable silicon wafers underneath. An empirical study from LightHief confirms this operational reality. Panels are usually situated far from processing hubs and face severe breakage risks during transport. Shattered components directly reduce material recovery rate and may be rejected or incur extra surcharges from recyclers (Lighthief International, 2026). This chain reaction severely damages the economic feasibility of high-value recovery.

5.4 The Value Mismatch

The fundamental conflict of the value mismatch is rooted in the WEEE Directive's initial design limitations. Its compliance structure is primarily tailored to short-lived consumer electronics with mature recycling pathways. The EoL management of these conventional appliances are built upon stable waste streams, relatively simple physical dismantling and mature processing technologies, allowing for steady economic returns from recovered materials (OECD, 2016). The weight-based metrics established by WEEE were designed to divert the large number of e-wastes from landfill and incineration, thereby reducing CO2 emissions and human and eco-system toxicity (Department for Business, Innovation and Skills (UK), 2013).

Yet, a solar panel is more than just another gadget. PV modules are durable energy-generation equipment built to last 25 to 30 years. Upon retirement, these panels still retain immense value, both for reuse in secondary markets and as a source of high-value strategic materials (Tao & Yu, 2015). However, since glass and aluminum frames together make up nearly 90% of a panel's weight, recyclers can easily pass the 80% recovery target by simply stripping the metal and crushing the glass. As noted in the official report on WEEE recycling targets from the European Commission, targets based on mass provide no incentive to extract materials found in trace amounts (European Commission, 2015). Consequently, critical elements with immense economic or strategic worth such as silver and silicon from the panels are lost or contaminated during the crude crushing process (Kastanaki & Giannis, 2022). What could have been a high-value recovery system ends up as a simple case of downcycling.

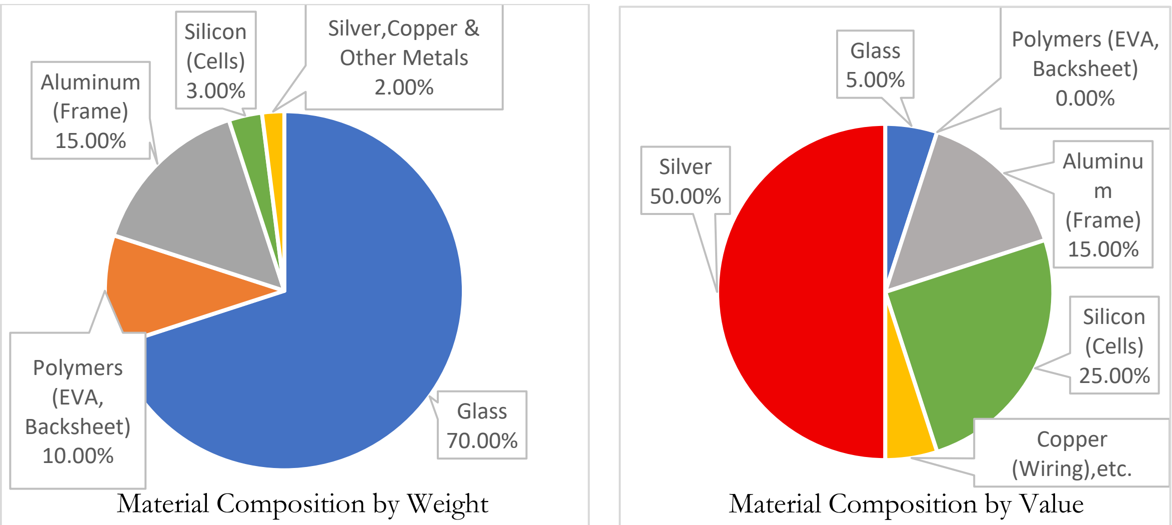

Figure 5-1. Comparison of Material Weight and Economic Value in Mainstream c-Si PV Panels

Note. Adapted from IRENA & IEA PVPS (2016) and Wu (2025)

Value Retention Theory and the R-strategies under the circular concept generally argue that reuse should come before recycling. Although notable technical exceptions exist for components like batteries due to severe safety and degradation issues, this value retention hierarchy remains highly applicable to structural and stable assets like PV panels. For this modules, reuse maximizes the retention of energy, materials and the engineering attributes from the manufacturing stage (Tao & Yu, 2015). However, within the WEEE framework, "preparing for reuse" and "recycling" are merged into a single 80% weight target. This creates a serious perverse incentive (IEA PVPS, 2025a). Without a separate target for reuse, operators naturally choose the cheapest way to meet the compliance requirements. The preparation for reuse would require the panels to go through a series of testing such as flash testing, insulation resistance testing and electroluminescence imaging to test the panels' usability and safety. These tests require professional and expensive equipment and there are no unified testing standards in the PV industry (Basnet et al., 2025). What's more, according to Solar Power Europe (2025), the price of new mainstream PV panels in EU reaches €0.11 per watt in early 2026, which is extremely low a price and nearly diminishes the profit from reselling old panels, let alone justifying the high testing costs.

On the data side, accurate figures for the reuse of retired PV panels are difficult to obtain across the EU. Nevertheless, there is a broad consensus that the reuse share is small compared to mechanical shredding. According to IEA PVPS (2024b), the reuse rate for the German market stands at 12.4%. This figure, however, is based on 2018 data and no longer reflects the current situation. Studies also confirm that Europe's domestic PV reuse market remains very small and presently restricted to the occasional supply of replacement parts for existing installations. Many panels are shipped to developing countries in West Africa and the Middle East without strict testing (Kastanaki & Giannis, 2022; Strupeit & Tojo, 2023). In France, Soren's latest annual data shows that in the total 5,207 tonnes of panels collected, about 90% are mechanically shredded (REN21, 2024). In the absence of effective testing and tracking mechanisms for reuse under the current framework and given the pressure to meet weight-based targets, operators naturally tend to shred heavy materials directly as a quick way to comply. As a result, the intention of extending the service life of panels can hardly be treated as a priority under the current WEEE system.

For solar panels entering the recycling stream, their core value is highly concentrated with trace amounts of metals and critical materials. As noted earlier, the EU's CRMA explicitly classifies high-purity silicon as indispensable for EU's strategic security. Meanwhile, silver, due to its high market price, constitutes the key economic driver for the recycling of PV panels. According to the quantitative models built by D'Adamo et al. (2023), in secondary material markets, silver price averages around €650/kg. Glass, which makes up the bulk of a panel's weight, sits at a negligible €0.125/kg.

Stripping these high-value materials from the panels is difficult. Current state-of-the-art technologies capable of high-purity recycling rely mainly on a combination of thermal treatment and hydrometallurgy. In order to dissolve the encapsulant (EVA) and extract silicon at a purity level of 99.999% alongside silver at a recovery rate of over 90%, recyclers need to pyrolyze the panels in a high-temperature furnace exceeding 500°C, followed by chemical etching using strong acids (Deng et al., 2019). This process is incredibly energy-intensive and expansive. Without substantial policy subsidies or higher PRO fees, recyclers cannot reach financial break-even by selling only the small quantities of silver and silicon recovered (IEA PVPS, 2025a).

Caught between the prohibitive cost of high-value material recovery and the low threshold for meeting weight-based targets, opting for downcycling is a rational and commercially driven compromise. Mechanical shredding destroys the very silicon crystal structures that could otherwise be purified. The valuable silver becomes irreversibly contaminated, lost among low-grade glass shards. Ultimately, these materials are downgraded to cheap construction insulation or simply dumped in landfills (Kastanaki & Giannis, 2022).

Overall, the weight-based recovery and recycling targets under the WEEE Directive fail to incentivize recyclers. Under this framework, prioritizing PV reuse and high-value recovery of strategic materials remains structurally out of reach.

6 Stakeholder Perspective and Discussions

Following the quantitative evidence in Chapter 5, which leverages data from three Member States to confirm the structural mismatch of the WWEE Directive across financial, logistical and value-recovery dimensions, this chapter initiates a qualitative inquiry into the underlying institutional drivers. Although documentary sources provide clear proof of existing misalignments, statistics alone cannot fully capture the complex interplay of stakeholder interests or the intricate operational challenges. Since the large wave of PV waste has not yet to come, much of the practical knowledge remains undocumented.

To bridge this gap, this chapter draws on semi-structured interviews with eight senior experts including policy researchers, representatives from PROs and recyclers and industry practitioners. These different perspectives compensate for data gaps, identify conflicts among actors and uncover grey areas currently escaping regulatory oversight. The insights are structured as an iceberg model illustrated in Figure 6-1, guiding the discussion from visible operational failures to strategic solutions.

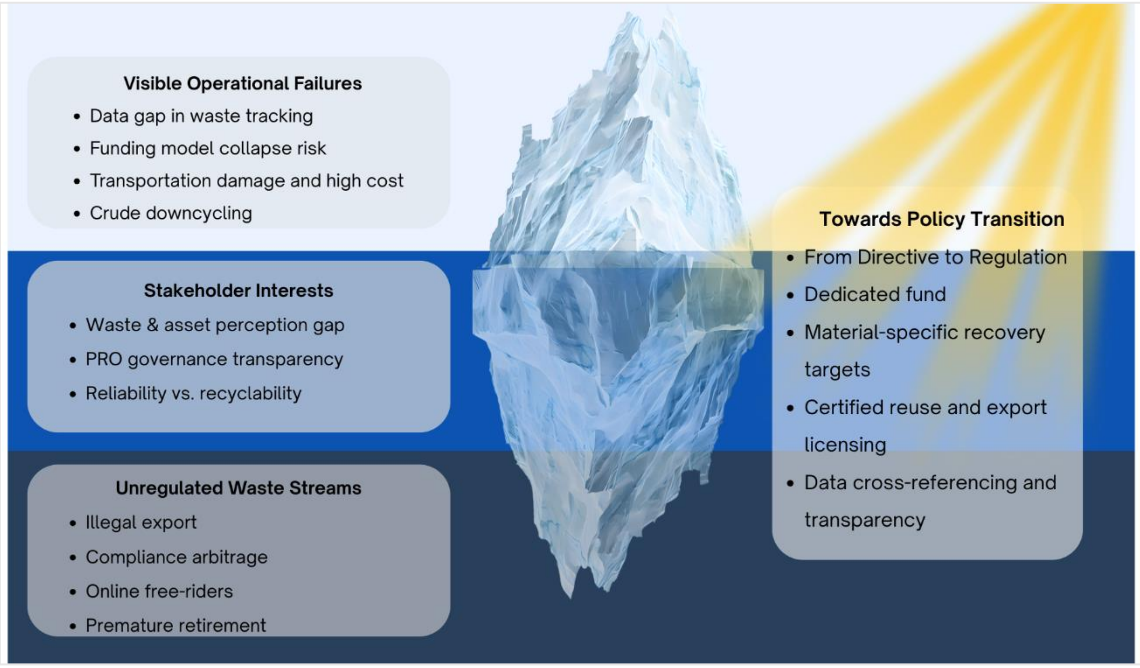

Figure 6-1. The Iceberg Model: A Summary of Qualitative Interview Findings

6.1 Visible Operational Dilemmas: Validating the Structural Mismatch

This section utilizes the practical experiences of the interviewed experts to validate the structural misalignments found in financial mechanism, logistics and high-value recovery. As depicted at the surface level of the iceberg model, these misalignments manifest directly as visible operational problems. In addition to verifying the existing arguments, the experts offered detailed practical insights into the underlying causes and possible solutions. These fresh perspectives deepen our understanding of the issue and lay a solid foundation for developing actionable policies later on.

Data Gap in Waste Tracking

Policymakers need detailed and accurate baseline data to identify management flaws and design effective solutions. When discussing the operational challenges, most interviewed experts, especially researchers, stressed the urgent demand for comprehensive data disclosure. They pointed out that the existing regulatory framework has critical data gaps in waste tracking. As a result, authorities are unable to accurately verify if the actual volume of decommissioned panels matches the amount entering compliant channels.

Expert E6 pointed out that current regulatory operations depend primarily on one-way reporting within the WEEE framework. Cross-department data validation is almost non-existent. For example, E6 advised that decision-makers should directly utilize and compare the specific dismantling numbers recorded by organizations such as the German Federal Network Agency (Bundesnetzagentur). Researcher E3 strongly supported this data-matching method. He argued for mandatory cross-checking between the actual decommissioning figures held by national grid operators and the declarations submitted by PROs. This step would effectively eliminate false reporting.

The lack of transparency in statistics leaves regulators without clear enforcement tools. It also creates room for equipment owners and recyclers to bypass compliance and allows retired panels to slip into grey export markets.

Funding Model Collapse Risk

Experts generally agreed that the pay-as-you-go financial model is inherently flawed for managing the EoL of long-term assets like PV modules. Researcher E3 highlighted a contradiction within the existing fee calculation logic. The low fee collected at present will eventually collide with a shrinking pool of future funding. On one hand, PROs calculate the EoL management fee based on the low PV waste collection rates today. E3 used Germany to illustrate this reality. With the current collection rate at just 12 to 15 percent, the fee is a mere 40 to 50 euros per tonne. This calculation method results in inadequate current financial reserves and fundamentally defers the massive actual disposal costs to the future. On the other hand, the smooth operation of this pay-as-you-go model relies heavily on a continuous boom in new PV installations to provide a financial safety net. However, E3 warned that future installation forecasts are somewhat optimistic. Many countries face severe grid capacity and infrastructure constraints and the growth momentum of new PV installations will likely slow down significantly in the next 10 to 15 years. This indicates that when the massive historically deployed panels are about to retire, the system is not able to draw enough money from sluggish new sales, leading to a major shortfall in recycling funds.

Furthermore, experts highlighted the pressing need for dedicated financial reserves for retired panels. E3 noted that aside from a few countries like France and the Netherlands that have established exclusive fund depositories, the majority of PROs continue to use a shared fund pool. Fees collected from PV panels are managed together with funds from other electronic waste streams. For example, this money could be allocated to process traditional household appliances. Ultimately, the lack of dedicated financial protection not only diminishes the transparency of PV-specific funds but also weakens the financial system's resilience against the impending surge in PV retirements.

Physical Damage and High Cost in Logistics

In discussing the logistics of PV waste, experts revealed the value destruction caused by improper handling and the economic dilemmas arising from dispersed geographical distributions.

First, unprofessional dismantling and transportation directly destroy the potential reuse value of retired PV modules. Expert E6 noted that on-site dismantling personnel usually lack specific operational guidelines. In pursuit of short-term efficiency, workers often cut the cables instead of simply unplugging them. They also stack the panels roughly during the loading process. This reckless source handling causes irreversible physical damage to the vast majority of panels before they even reach processing facilities. As a result, it eliminates the possibility of repairing them for the secondhand market.

Next, when evaluating overall logistics and warehousing costs, experts responded differently. Industry practitioner E7, representing large centralized solar farms, argued that unified handling and bulk transport do not present substantial operational barriers in projects with strong economies of scale. However, other experts described a completely different reality for decentralized and remote waste collection. Taking the US market as an example, researcher E2 pointed out that vast geographical spans and highly expensive labor make the costs of transporting scattered waste panels from remote areas prohibitively high. Researcher E4 added that even if operators overcome the basic physical transport difficulties, attempting to elevate the logistics network in order to support high-value recycling or reuse incurs massive supplementary expenses. The high cost of professional storage, sorting and the individual unit performance testing would render the operation economically unfeasible. The absence of economies of scale, combined with high supplementary expenses, forms a critical logistical bottleneck in PV EoL management.

Crude Downcycling Driven by Weight-based Targets

In examining the high-value recovery of retired PV panels, interviewed experts severely criticized the existing compliance framework. Specifically, they pointed out that purely weight-driven recovery targets cause severe losses in critical and high-value materials.

Recycler representative E5 explained the root cause of this loophole. He noted that the physical composition of PV panels consists of 70 to 80 percent glass and 10 to 15 percent aluminum. In contrast, materials like silver, silicon and copper that capture the majority of economic value account for a merely marginal percentage of the weight. To control processing costs and meet the required recovery and recycling targets, recyclers can easily comply by simply removing the aluminum frames and mechanically shredding the remaining panels. Through on-site observations, E3 confirmed this operation reality. He mentioned that once the weight requirements are met, recyclers often send the impure glass fragments straight to landfills.

In response to these superficial recycling practices, researcher E4 expressed his concerns about the negative consequences for the circular economy. He emphasized that materials with tiny weight percentages but major economic and strategic value like silver and high-purity silicon, are completely mixed and downgraded during low-cost bulk shredding. In many cases, they are permanently lost. Collectively, the experts concluded that a policy framework fixated entirely on weight-based metrics obstructs the industry's transition toward high-technology and high-value recovery and limits the circular utilization of materials.

6.2 Divergent Interests: The Conflicts Among Stakeholders

In the management of PV EoL, various stakeholders held different perspectives and stances regarding product definition, responsibility allocation and product design. These differences are mainly driven by their roles and economic interests. A deep understanding of their respective interests and positions is necessary to pinpoint gaps in the current management system and provide guidance in improving future policy and compliance frameworks.

Differences in Product Characterization

Regarding the characterization and lifecycle management of PV modules, the deployment and recycling sectors demonstrate distinct priorities based on their respective professional stances. Industry practitioner E7 emphasized that PV modules are essentially key financial assets that generate continuous cash flow. Their long-term investment return far exceeds their material costs. From the EoL management point of view, researcher E2 noted that because panels contain a large portion of low-value glass and plastic, they are bulky and contain minimal value upon decommissioning. Taking into consideration these physical properties and processing difficulty, they resemble cheap construction waste. She believed that the rational way is to maximize the service life of PV modules and improve their long-term reliability.

Despite the different focal points from these two experts, one consensus is the long-term heavy asset nature of PV panels. Whether seen as long-serving financial assets or as bulky low-value waste, PV panels are fundamentally different from conventional short-lived consumer electronics. To regulate this long-lived, durable industrial product under the WEEE framework, which was primarily designed for short-lived consumer goods, creates an inherent mismatch.

PRO Governance and Path Dependency

When discussing responsibility allocations, interviewed experts pointed out that governance flaws and vested interests within current PROs severely obstruct the stability and advancement of the recycling system.

Researcher E3 outlined the root causes of this issue. He pointed out that the management boards of many PROs are led by module importers instead of recyclers or government organizations. The core objective under such governance structure is to keep the current compliance fee as low as possible to maintain price competitiveness of the new products in end markets. This operational model oriented towards controlling short-term costs has led to a strong path dependency in PROs. To sustain low fees, these organizations naturally resist system upgrades that would increase compliance costs, such as establishing dedicated PV funds or investing in high-value recycling technologies.

This path dependency directly drives short-sighted compliance practices. Regarding fund management, most PROs utilize a mixed funding pool model. Because the massive decommissioning of PV panels is still a decade away, large amounts of compliance funds collected today from new PV installations are often used to manage current influxes of conventional electronic waste. Although this operation relieves financial pressures in the short term, in essence it drains the funds reserved for addressing the future wave of PV waste. For physical processing, PROs tend to maintain low-cost methods by mechanical shredding to meet minimum weight-based compliance targets.

E3 expressed a further concern. PROs serve as the primary source of industry data for regulatory bodies like the European Commission. Since they benefit from the current low-cost model, they lack the motivation to accurately report the long-term risks accumulating within the system. They tend to remain silent on structural flaws such as the funding gap, leading to severe information asymmetry for regulators. E3 warned that when the large-scale waste wave eventually hits in 20 years, these management bodies could easily evade their historical responsibilities for their prior mismanagement by blaming external global force majeure factors.

Trade-offs Between Reliability and Eco-design

The European Union strongly advocates for eco-design, recognizing that early-stage material and structural choices fundamentally dictate downstream recycling efficiency. However, within this context, experts pointed out a clear gap between the physical demands of long-term PV panels and the current circular design principles. This discrepancy demonstrates the practical challenge of applying recycling-focused design models to long-lasting infrastructure.

First, there is a conflict in product design between physical reliability and material reduction for PV panels. E2 addressed that the physical reliability of PV panels must be the primary design priority. She observed that some manufacturers, in order to reduce logistics costs, implement lightweight design such as decreasing glass thickness from 3 mm to 2 mm. While this design aligns with the material efficiency goals advocated by policymakers, it significantly increases the risk of panel breakage during operation and thereby generating a large amount of premature waste. Researcher E6 added that current mainstream panels are already highly durable and pushing for design changes oriented toward recyclability is not an immediate industry necessity.

Furthermore, the implementation of eco-design principles faces obstacles regarding cross-border jurisdiction and field engineering priorities. Researcher E6 pointed out that enforcing mandatory regional eco-design regulations is difficult in operation because the vast majority of global PV manufacturing capacity lies outside of the European jurisdiction. In solar projects execution, PV design choices are often dictated by the immediate administrative requirements. Industry practitioner E7 confirmed that during the evaluation and construction phases of solar farms, engineers focus mainly on more imminent compliance requirements such as biodiversity protection that impacts project commencement. Given the average 30 years' service life of PV projects, eco-design considerations for decommissioning are typically marginalized within current operational priorities. The globalized manufacturing chain and immediate compliance pressures further prevent the idealized eco-design visions from gaining substantial traction in the PV sector.

6.3 The Grey Zones: Waste Streams Beyond the WEEE Directive's Reach

During discussions with experts regarding the actual effectiveness of the WEEE Directive in regulating PV EoL, multiple interviewees indicated that certain waste streams are escaping official tracking and legal constraints, undermining the practical impact of European circular economy strategies.

Illegal Export and Cross-border Waste Dumping

At the collection stage of decommissioned panels, a network of unqualified brokers forms a grey market. According to E5, uncertified brokers visit solar farms with cash to acquire retired modules at prices higher than those offered by certified recycling channels. These panels are then shipped to Africa or the Middle East without regulatory oversight. E4 also pointed out the legal cover for this supply chain. He observed that project owners often sell panels as second-hand products at low prices in B2B transactions. Since these panels are not classified as waste, they easily bypass strict export requirements for electronic waste. Researcher E3 claimed that at least half of the collected retired PV panels are exported out of Europe under the pretext of reuse, yet they usually end up in local landfills after brief testing. Policymaker E1 emphasized that this unregulated export not only causes environmental pollution to developing and underdeveloped countries but also deprives Europe of control over critical strategic raw materials, contradicting the intention of circular economy to keep resources within its borders.

Compliance Arbitrage in B2B Channels

The differentiated management of B2B and B2C PV products under the WEEE Directive creates an institutional loophole for companies to shift financial responsibilities. According to E6, while Germany imposes very strict rules on the classification of B2B PV panels, B2B producers need only offer a recycling plan. End-users are not obliged to return the panels, resulting in an extremely low collection rate for commercial PV waste. E3 revealed a more direct form of financial arbitrage. He pointed out that in certain Eastern European countries, up to 90% of companies act as free-riders by claiming their panels as non-residential products. In response to this loophole, E4 criticized the different legal requirements between B2B and B2C PV panels and the chaos this differentiation has caused in PV waste treatment. He argued that all PV panels placed on the market should be forced to bear the same legal responsibility in their EoL management.

Online Free-riders

With the rise of digital trade, online direct sales that are not subject to territorial regulation have emerged as another major blind spot. E6 mentioned that even though some countries have required e-commerce platforms to verify sellers' WEEE registration and have successfully reduced free-riding, the reach of regulatory oversight is still limited. Cross-border direct sales that bypass all e-commerce platforms and sell directly from outside the EU to European end-users remain extremely difficult to track and regulate. These invisible sellers place PV modules on the European market and completely evade their financial obligations for PV EoL management.

Premature Decommissioning

Despite years of repeated calls from academia and industry organizations to optimize PV EoL management, the current regulatory framework has yet to undergo substantive reform. Since PV modules have long lifespan and the large-scale of waste surge still appears to be a future risk, policy reforms can always wait until tomorrow. However, a capital-driven force is now disrupting this policy inertia. E8 observed a strong repowering trend in the market, driven by the pursuit of higher power output and faster returns of investment. As a result, many modules are prematurely dismantled after only 5 to 7 years of service. E3 added that due to the extremely low price of new modules, replacing them after a short time is financially viable in certain areas. This capital-driven premature retirement generates a massive volume of early waste. As a result, this sudden influx threatens to completely overwhelm both current regulatory tracking system and physical recycling facilities.

6.4 Towards Policy Transition: Consensus and Reconstruction Pathways

During in-depth discussions with various stakeholders, several constructive reform strategies were proposed to address the structural flaws of the current management framework. The consensus built on practical experience provides a solid foundation for the systematic policy recommendations presented in Chapter 7. The following section outlines five strategic priorities for policy reconstruction.

Regulatory Framework Update

To address the fragmentation due to transpositions of the WEEE Directive across member states, interviewee E6, E3 and E4 all suggested EU to introduce a unified Regulation with direct legal application. This regulation would replace the current Directive and eliminate frictions and execution discrepancies caused by different interpretations. E1 also advocated for smart and simplified rules aimed at reducing unnecessary administrative burdens while maintaining the core regulatory standards.

Financial Mechanism Reform

Researcher E4 advocated collecting full compliance fees during the initial stage of market entry. Through the establishment of a dedicated PV reserve fund, these collected fees can be invested throughout the 30-year lifespan of the PV modules to achieve capital preservation and appreciation. This approach ensures robust financial backing in facing future large-scale decommissioning and fundamentally resolves the current lack of long-term financial planning.

Recovery Target Adjustment

The weight-based recovery and recycling targets are widely considered to be the fundamental barrier to high-value recovery of electronic waste. E4 and E5 both strongly called for a shift toward material-specific recovery requirements. E4 specifically noted that future regulatory targets should set mandatory recovery rates for specific materials such as aluminum, glass, silver and silicon. This can effectively incentivize companies to invest in advanced processing technologies, thereby enabling recyclers to achieve financial independence and commercial viability by extracting and selling high-value, strategic materials.

Reuse Market Regulation

To combat illegal exports disguised as second-hand trade, regulatory bodies urgently need to establish accurate tracking and prevention mechanisms. E6 recommended that customs departments should refine tariff codes to strictly distinguish second-hand and new panels, monitoring at borders to stop illegal dumpling. At the same time, reuse market needs to be regulated. E2 suggested establishing a mandatory certification system for retired modules entering the second-hand market. This system should incorporate standardized technical testing procedures focusing on the assessment of the physical integrity and electrical insulation safety of the modules. A standard certification system can drive fragmented second-hand testing operations towards centralization, thereby creating economies of scale in the testing and refurbishment sectors. In the end, this guarantees the long-term commercial and economic viability of a legitimate reuse market.

Data Tracking and Transparency

Enhancing data transparency across the entire value chain is viewed as the principal method to tackle compliance arbitrage and false reporting. Building upon the cross-validation method mentioned earlier, E3 further advocated that regulatory bodies should not rely on single data sources but establish a comprehensive verification network covering multiple stakeholders. Extensive data collection and cross-referencing should be carried out by national WEEE registration systems, PROs, manufacturers, recyclers and grid installation departments. Industry practitioner E7 said that existing supply chains now are fully capable of implementing Digital Product Passports for a full lifecycle traceability. E4 pointed out that the ultimate goal of these digital tools should be to serve close-loop resource management, ensuring that critical raw materials are kept within Europe for circular reuse and recycling.

7 Recommendations and Conclusion

7.1 The Ultimate Goal: A Dedicated EU Solar Asset Regulation

As repeatedly argued in previous chapters, the WEEE Directive operates as an EoL regulatory framework tailored for short-lived consumer electronics. It is fundamentally ill-equipped to govern PV panels, which function as durable energy infrastructure and investment assets. To resolve this structural mismatch at its core and prepare the EU for managing the impending surge of solar waste, policymakers should initiate three major macro-level shifts.

Separating PV from WEEE

The first shift is to separate PV modules completely from the WEEE framework and establish a dedicated regulation for PV EoL management. Long-lasting energy-generating assets exhibit entirely different financial operations and EoL pathways compared to ordinary household appliances that consume electricity. Forcing both categories into the same regulatory framework inevitably causes management ineffectiveness.

From Directive to Regulation

The second shift means to elevate the legislative level. As advocated by most of the interviewees in Chapter 6, the WEEE Directive operates merely as a framework law. It requires individual Member States to transpose it into national legislation. This allows excessive operational leeway, resulting in regulatory ambiguity and execution fragmentation across Europe. This thesis proposes upgrading the current directive into a unified EU regulation with a reasonable degree of operational details. A unified regulation with direct legal force would effectively eliminate the execution chaos. Furthermore, for producers selling across multiple EU countries, this would significantly reduce the administrative burden and for recyclers, it would facilitate a smooth cross-border flow of decommissioned PV panels for functional reuse and high-value recovery within the EU.

Removing Application Distinctions

The third shift involves completely removing the classification boundaries between commercial and residential application scenarios. The new regulation should no longer distinguish between B2B and B2C applications. Instead, it must include all decommissioned PV panels into a unified EoL management system without exception. As mentioned before, commercial and industrial rooftops alongside utility-scale solar farms constitute the absolute majority of EU PV deployment, accounting for 81% of the total market share (SolarPower Europe, 2024). Driven by the global clean energy transition, the scale of large, centralized PV installations most likely will continue to expand. The WEEE framework takes a relatively lenient approach for B2B equipment by allowing producers and project developers to determine future waste management responsibilities through private contracts. Given the decades-long service life of PV modules, such private agreements lack external regulatory oversight and are extremely difficult to track and enforce. Exempting the dominant PV B2B sector from strict financial and compliance constraints would fundamentally compromise the integrity and effectiveness of the entire PV EoL management regulation.

7.2 Proposed Regulation Interventions Along the Lifecycle

Building on the three strategic macro-governance shifts established in 7.1, this section elaborates on the targeted regulatory interventions applied across the upstream, midstream and downstream stages of the PV panel value chain. This multi-tier framework ensures that the PV EoL management achieves high synergy and operational efficiency throughout the entire product lifecycle. Figure 7-1 below illustrates these regulatory intervention measures.

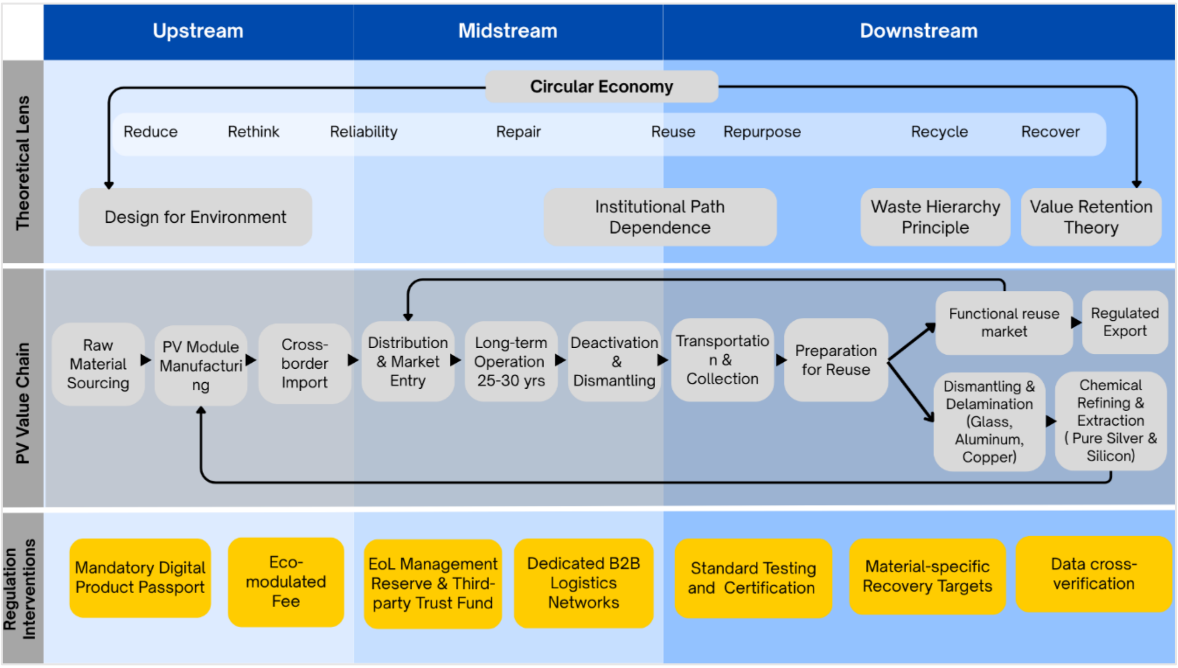

Figure 7-1. Policy Interventions across the PV Lifecycle

Upstream Interventions: Data Transparency and Design Alignment

Mandatory Digital Product Passports

The EU has recently introduced the concept of the DPPs under the ESPR. Importantly, this concept has already materialized into binding law through the mandatory Battery Passports under the new EU Battery Regulation. Implementing a similar, legally binding DPP mechanism for PV module is the first step to eliminating information barriers across their lifecycle. Specifically, all panels entering the EU market must register their material composition in detail, including the correct proportions of critical metals like silver, silicon and copper. Manufacturers should also detail the encapsulation specifications for glass and polymer back sheets and provide standardized dismantling guidelines. This information is logged into a central database. Each panel will then receive a unique digital identity linked to this data via a QR code or RFID chip, mirroring the precedent set by the battery sector.

Implementing DPPs bridges the information gap caused by the decades-long service life of PV panels. Accurate upstream material data can be transferred seamlessly to downstream recycling facilities. This continuity provides clear technical instructions for safe dismantling operations. With the original material specifications, recyclers are also able to perform high-value extraction of specific materials and enable comprehensive data cross-verification across the entire closed-loop value chain.

Eco-modulated Fee

An essential measure to incentivize manufacturers at the design stage and improve EoL outcomes is the introduction of eco-modulated fees. The legal foundation for this mechanism is rooted in the EU Waste Framework Directive (2018/851)[6], which requires Member States to modulate financial contributions paid by producers based on specific lifecycle criteria such as durability, reusability and recyclability (European Union, 2018). France has been a pioneer in translating this directive its Anti-Waste for a Circular Economy Act (AGEC).[7] According to Micheaux and Aggeri (2021), the Frech model shifts the focus of EPR from a mere waste-financing tool to a dynamic governance instrument that internalizes environmental externalities. More precisely, this system adopts a "Bonus-Malus" structure where fees are adjusted based on the presence of "recycling disruptors" or the integration of recycled content. For example, producers pay a financial penalty (Malus) for technical choices that complicate the sorting and recycling processes while receiving a discount (Bonus) for designs that enhance material circularity.

Within the PV sector, the French PRO Soren provides a highly successful operational model. Soren applies a strict eco-modulation fee structure to all PV modules entering the French market. The financial contribution per panel is determined by evaluating key environmental metrics, specifically focusing on the module's carbon footprint, the quantity of silver used and the share of incorporated recycled materials and the lead content (Soren, 2025a). Building upon accurate information such as the data provided by DPPs, this system executes a precise framework of financial rewards and penalties. If a manufacturer adopts encapsulation technologies that facilitate easy delamination, eliminates toxic substances like lead, minimizes silver consumption and enhances overall physical reliability, a substantial financial discount on the mandated EoL management reserve will be given to the manufacturer. On the contrary, producers face significant recycling penalties if their modules rely on complex composite materials that prohibit material recovery.

The core objective of this measure is to operationalize Design for Environment principles through financial leverage. The technological pathway for mainstream PV panels is already highly mature. Relying solely on enforcing administrative barriers such as denial of market access to compel manufacturing changes is most likely ineffective. Such rigid approaches could potentially disrupt the global supply chain and ultimately hinder the pace of PV deployment required for the European energy transition. Eco-modulated fee offers a pragmatic alternative. It incentivizes manufacturers to weigh in the initial production expenses against future compliance liabilities right at the research and development stage. Driven by pure commercial logic, it effectively reduces the generation of waste that are difficult to treat.

Midstream Interventions: Reconstructing Institutional Infrastructure

EoL Management Reserve & Independent Trust Fund

This thesis proposes to establish a dedicated EoL management reserve for PV panels, overseen by an independent third-party trust fund. Under this financial mechanism, producers are required to pay a sufficient amount as an upfront environmental fee the moment their products enter the market. This prepayment guarantees full financial coverage for the collection and high-value recovery costs that will be incurred 20 to 30 years in the future. Once collected, the capital is transferred to a specialized trust fund independently operated from any manufacturers or

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[6] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, OJ L 150, 14.6.2018, p. 109–140.

[7] Loi n° 2020-105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire [Act No. 2020-105 of February 10, 2020 relating to the fight against waste and the circular economy], JORF n°0035, 11 February 2020.

governmental institutions. This trust fund manages the locked funds and ensures long-term asset preservation.

The root cause for restructuring this financial mechanism is the structural mismatch between the pay-as-you-go system commonly used for traditional consumer e-waste and the exceptionally long operational lifespan of PV panels. This time and financial asymmetry put future PV waste management at the risk of funding collapse. Mandating a prepaid reserve managed by an independent trust fund ensures sufficient capital will be available to process retired panels. By securing this funding upfront, it effectively prevents the massive treatment costs of orphan products from falling onto municipal governments following company bankruptcies. It also provides robust financial backing for downstream high-value recovery. A trust fund can preserve and grow the PV capital pool overtime, helping to offset inflation and potential cost increase over time. Removing the control of these substantial funds away from PROs is conductive to breaking the black box of their internal financial operations and improving transparency in how funds are used and how external contracts are outsourced.

Dedicated B2B Logistics Networks

To optimize the collection and transportation of retired PV modules and ensure smooth integration with subsequent reuse and recovery processes, a dedicated B2B logistics network is essential. This network is managed entirely by industry professionals and bypasses standard municipal e-waste collection channels. As PV CYCLE (2023) advocates, the physical dismantling of decommissioned PV systems must be handled by qualified professional installers or maintenance companies within a strict B2B environment. The decommissioned panels first go through sorting, visual inspections, electrical testing and safety checks on the site to identify their reuse potential. Following the on-site triage, panels then are transported directly from the site or consolidation hubs to specialized recycling facilities. To address the geographical dispersion of PV deployments, the transport network should also flexibly distribute its collection hubs based on regional installation density to guarantee cost-effective coverage in remote areas.

There are three main drivers behind the implementation of a dedicated B2B logistics network. First, the dismantling of PV systems involves significant high-voltage electrical hazards. This requires professional handling to ensure operational safety. Second, PV modules are bulky, heavy and contain fragile glass components. Mixing them with conventional electronic waste in municipal networks frequently leads to physical damage of panels. This eliminates their potential for reuse and the retrieval of high-purity valuable materials. Third, standard municipal collection points may lack the capacity and resources as well to process massive influxes of PV waste. In comparison, a dedicated B2B system resolves these limitations. By coordinating logistics collectively through professional industrial channels rather than public utilities, the network can adapt to the uneven geographical distribution of solar deployments. It also allows panels to be consolidated and processed closer to the source, improving overall cost-effectiveness.

Downstream Interventions: Multi-tier Value Recovery

Standard Testing and Certification for Reuse

As discussed in early chapters, the current EU PV reuse market lacks scale and operates largely within an unregulated, chaotic grey area. Establishing a standardized testing and certification mechanism is the prerequisite for regulating and expanding this market.

This certification should define strict technical thresholds for modules entering the reuse stream. All panels should be professionally repaired and tested with comprehensive tracking documents proving their safety and performance compliance before getting cleared for resale or cross-border export. This unified standard will provide the customs and environmental agencies with clear enforcement criteria to accurately distinguish viable secondhand products from illegal e-waste. As a result, this will significantly curb the prevailing practice of exporting untested panels to developing countries under the guise of legitimate reuse. Paired with a set of complementary market incentives, this certification enables the EU to foster a compliant, transparent and economically scalable PV reuse market. Ultimately, this approach will drive the solar sector toward true circularity.

Material-specific Recovery Targets

The weight-based recovery metrics lead to low-cost mechanical shredding of retired PV panels. This crude downcycling causes the permanent loss of critical and high-value materials such as silver and silicon, contradicting the EU's circular economy strategy. To reverse this trend, the weight-based targets need to be replaced with material-specific recovery requirements.

In practice, regulatory authorities should set independent and legally binding extraction rates for key materials embedded within PV modules. Specifically, mandatory recovery rates should be established respectively for materials including silver, high-purity silicon, glass and aluminum. To ensure economic feasibility, mandatory targets should initially be set at modest thresholds and then gradually escalate as recycling technologies and infrastructure mature. Under these mandatory recovery metrics, recyclers will have to upgrade their processing technologies. By combining mandatory legal requirements with targeted financial subsidies, policymakers can drive long-term investment into industrial upgrades. Ultimately, recyclers achieve economic viability by supplying high-purity secondary silicon and silver back into the market, truly closing the loop on the PV value chain.

Data Cross-Verification

To solve the data opacity and fragmentation problem in PV EoL management, establishing a comprehensive data cross-verification mechanism is key. This mechanism systematically links four critical data collection nodes along the physical lifecycle of PV modules. They include DPPs data provided by manufacturers, installation and decommissioning records from grid operators, treatment reports submitted by PROs and recyclers and export tracking data from customs.

Authorities could cross-check the actual retirement volumes registered by the grid against the total intake volumes entering legal recycling and export channels. This ensures that no retired modules are unaccounted for, effectively preventing the leakage into the grey market. They could also match the total amount of high-purity silicon, silver and other critical materials recovered by recyclers with the original material composition ratios provided in the DPPs. This end-to-end validation effectively monitors the high-value recovery operations at the recycling facilities.

Although creating a dedicated EU regulation for PV EoL management is the most thorough way to fix the structural mismatch, a complete system overhaul may face heavy administrative burdens and stakeholder resistance due to institutional path dependency and the significant sunk costs Member States have already invested in the current WEEE system. Given these practical concerns, a workable compromise is to designate PV modules as an independent product category within the existing WEEE framework and translate the detailed policy interventions proposed above into specific rules for PV waste. By utilizing existing administrative structure, this alternative provides a solid legal foundation for the upcoming PV waste surge at a lower political and economic cost.

7.3 Conclusion

This study tackles the core policy dilemma in PV EoL management. Policymakers originally designed the EU WEEE Directive for short-lived consumer electronics. Applying this framework to solar modules, which can operate for up to 30 years, ignores their underlying physical and economic differences. To answer the first research question concerning misalignments between policy and reality, this thesis identifies a deep structural contradiction. Drawing on literature, industry data from three representative markets including France, Germany and Sweden and in-depth stakeholder interviews, the findings show that the current system mistakenly treats massive and complex energy-generation equipment as standard household waste.

Regarding the second research question, the evidence confirms that these misalignments severely damage financial viability, logistical efficiency and value recovery. Financially, the short-term pay-as-you-go operational logic is incapable of bridging the lifecycle gap spanning several decades, thereby exposing the entire recycling system to the risks of funding collapses and a widespread accumulation of orphan waste. Logistically, municipal collection networks are practically unequipped to handle massive and highly dispersed PV modules. High logistics costs, coupled with rough and unprofessional handling, eliminate the potential for these retired modules to enter the secondhand markets. Regarding value recovery, mass-based compliance targets create strong perverse incentives. Operators opt for crude mechanical shredding merely to meet legal quotas at the lowest possible cost. This approach leads to the permanent loss of critical and valuable materials like high-purity silicon and silver, fundamentally contradicting the strategic vision of the EU circular economy and the principles of value retention.

In response to the third research question on necessary policy interventions, having identified the three misalignments and their operational impacts, this thesis believes that incremental fine-tuning of the WEEE Directive will no longer suffice. To better prepare for the forthcoming PV decommissioning wave, the EU should separate PV modules from the WEEE framework and enact a dedicated regulation in managing PV EoL. Furthermore, lawmakers must eliminate the legal divide between commercial and residential obligations, brings the massive volume of B2B modules under one unified compliance system.

Practically, this requires interventions across the entire product lifecycle. Upstream, the industry should adopt DPPs to give recyclers exact materials data and dismantling guidelines. Authorities should simultaneously introduce eco-modulated fees to push manufacturers toward better eco-design. Midstream, securing financial sustainability means collecting sufficient management fees upfront and holding them in independent trust funds. Creating dedicated B2B logistics networks will protect these funds and keep the physical modules intact. Downstream, the market needs a unified certification system for secondhand panels. Regulators must also replace the volume-based metrics with material-specific recycling targets. Finally, cross-verifying data among DPPs, grid operators, PROs and recyclers will prevent old modules from slipping into the grey market while tracking high-value materials.

Although this thesis provides a new regulatory blueprint, implementing it requires further research. First, the independent trust fund needs long-term financial modeling to determine reasonable prepayment rates that can withstand inflation and cost fluctuations. Second, future work should explore the practical application of DPPs across transnational supply chains to enable cross-border data transfer while protecting corporate trade secrets. Finally, the engineering community needs to collaborate on establishing globally recognized testing standards for PV module reuse, thereby providing a scientific foundation for the safe redeployment of decommissioned modules.

In summary, these policy shifts aim to move PV EoL management toward genuine value retention. By embracing this transition, decommissioned panels will achieve maximum value through reuse and high-value material recovery. Ultimately, this closed-loop approach liberates decommissioned PV modules from the structural mismatch of the WEEE Directive, establishing a truly self-sustaining circular economy for the EU solar sector.

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Appendix A: Interview Protocol

Thesis Name: Structural Mismatch in EU PV End-of-life Management
Date and Time: **Location**: online
Interviewer: Fan Liang **Interviewee Code**:
Stakeholder Category: **Target Market**:

Introduction & informed consent:
Thank you for taking the time to speak with me today. Before we start, I'd like to introduce briefly what my thesis is about. The title is The Structural Mismatch of the WEEE Directive in Managing PV EoL. My idea is that WEEE is designed for short-lived consumer electronics and may not be the best fit in managing PV waste that is large, heavy with a super long lifespan and high values in reuse and recycle scenarios. We'll go over the possible mismatches in terms of the financial guarantee mechanism, logistics and the value recovery in the interview questions.
The interview will take about 45 to 60 minutes. You can skip any question or stop at any time. With your permission, I'd like to record the session so I don't miss anything. The recording and transcript will be kept confidential and fully anonymized in the final thesis.
Do I have your consent to record? Thank you.

Questions
Warm-up
1. From your LinkedIn profile, I see that you have been working in the energy sector sustainability for many years. Before we begin could you briefly introduce your background and your experience in PV industry or PV EoL?
2. With the rapid deployment of solar energy across Europe, we are anticipating a significant surge in PV waste as early installations begin to reach their end of life. Could you share your perspective on how PV waste is currently managed in Europe and what we might expect over the next 10-15 years?

General questions (validate the mismatches listed in Chapter 5)
3. This question is about the WEEE Directive's financial guarantee mechanism. Producers have three compliance options: 1) lock a bank guarantee for the module's lifetime, 2) pay annual insurance, or 3) join a PRO and pay an annual fee. Critics argue that locking away large sums is commercially unreasonable, and that annual PRO fees—which cover current waste management—won't be enough when the PV waste surge hits. What's your view on the financing mechanism for PV waste?
4. Regarding logistics: PV panels are heavy, require professional dismantling, careful transportation, and proper storage. They are also usually installed in remote and dispersed locations. Are there any issues with the current logistics arrangements for PV waste, compared to household electronic waste?
5. The WEEE Directive sets an 80 percent recovery target based on weight. In practice, how are recyclers handling this right now? Are facilities mostly just crushing the glass to hit the numbers, or is anyone really focusing on functional reuse and extracting critical metals like silicon and silver?
6. When we talk about waste management, we always refer to the waste hierarchy: repair, reuse and recycle, do you see PV panels being able to follow such a hierarchy? Are there any technical or economic obstacles?

7. Regarding the recovery of high-value materials like pure silicon and silver. Many research say that it is not economically and technically viable now. Do you think it is absolutely necessary to retrieve the trace amounts of silicon and silver in the panels?
8. In your opinion, what would be the ideal way of managing PV EoL in Europe?

<u>Category-specific questions (industry opinions)</u>

For policymakers and researchers:

9. We see different countries applying the WEEE rules for PVs differently, for example, France government mandated Soren to be the only PRO handling only on PV panels and Germany have just one organization that send pick-up orders to producers and the producers are responsible for the rest of the waste management. In your opinion, is there a national model that you think is more effective?
10. What's your view on giving member states greater flexibility in interpreting the WEEE Directive according to their domestic situations — is this a positive or negative development?
11. From a legislative standpoint, what is the biggest political or institutional barrier to revising the legislative requirements for PV EoL?

For PROs and recyclers:

12. As someone handling the actual operations, how severe is the issue of physical damage to the panels during collection, especially when relying on standard municipal e-waste centers?
13. Are there any subsidies in running the PRO/recycling facilities? Is it currently economically viable for a recycling facility to invest in specialized technology to recover high purity silicon and silver, rather than just doing basic mechanical shredding?

For producers:

14. The WEEE Directive allows for national transpositions, leading to different registers, fees, and B2B/B2C classifications across Europe. How do these variations affect your daily operations and costs?
15. Technically and commercially, is eco-design for solar panels feasible? And what do you think of an EU rule that requires reuse potential to be built in at the manufacturing stage?

<u>Future solutions</u>

16. Looking ahead to policy reforms, if you could change one thing in the current WEEE framework for solar panels, what would it be and how would you change it?
17. If I were to propose to establish a new directive only for Solar, like the one EU has for battery, would you say it is a valid proposal or not necessary?

<u>Closing</u>

18. Are there any other critical challenges or upcoming policy shifts regarding PV waste that we have not discussed today?

Appendix B: Declaration of Use of Generative AI (GAI) Tools

Project/Assignment title: Structural Mismatch: the EU WEEE Directive and Photovoltaic End-of-Life Management

Did you use GAI tools for this work? ☒Yes ☐ No

If Yes, complete the items below.

a) Tools used

List the tools and versions (e.g., "ChatGPT, Claude, DeepL"):

Gemini (Version: Gemini Pro) Kimi (Version K2.6)

b) What you used them for (check all that apply)

☐Brainstorming / idea generation
☒ Planning / structuring
☒Language editing (grammar/clarity)
☒Translation (non-sensitive content)
☐ Outline drafting
☐ Other (specify): ______________________

c) How you used the tools (be specific)

Describe prompts, steps taken, and how you revised the outputs:

I provide my drafts of the thesis chapters such as the Conclusion, Methodology and Policy Recommendations and prompted the GAI to polish the academic tone, ensure grammatical accuracy and improve sentence flow. Some parts of the non-sensitive drafts I wrote in Chinese (my native language) and asked GAI to translate into academic English. I then revise the translated version to make sure they followed my logic and are the right tone I wanted. I use GAI to ask advice on thesis structure and advice to improve my figures and tables design.

d) Your own contributions

What parts are entirely your original work?

All core intellectual contributions are entirely my own original work. This includes the formulation of the research questions, the development of the three-dimensional lifecycle governance framework, the design of the qualitative interview protocol, the integration of

all quantitative market data, the analysis of the structural mismatches and the formulation of the final policy recommendations. The GAI was largely used as a language and formatting assistant.

e) Verification and editing

How did you verify accuracy and edit AI output?

I reviewed every sentence output by the GAI to ensure it accurately reflected my academic intent. For example, during the language editing phase, the GAI incorrectly used the term "theoretical gaps". I identified this conceptual error and manually corrected it to "structural misalignments" to accurately match the core thesis argument. All output were heavily edited to match my personal writing style before final integration into the thesis.

Student signature: Fan Liang Date: May 15, 2026