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Economics and Environmental Impacts of Photovoltaic Panel Recycling in Germany

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Abstract

The rapid expansion of solar photovoltaic (PV) deployment has led to increasing concerns regarding end-of-life module management and the sustainability of material supply chains, where waste volumes are projected to reach 3.3–5.6 million tons by 2045. This study evaluates the environmental and economic impact of advanced photovoltaic recycling in Germany, focusing on high-value material recovery from crystalline silicon modules. A Full Recovery of End-of-Life Photovoltaics (FRELP) pathway is developed, integrating light-pulse delamination and molten salt etching, and a comparative life cycle assessment and economic assessment framework is applied. The results indicate that advanced recycling achieves high recovery rates for silicon, silver, aluminum, copper and low-iron glass, yielding around €1174.88 per ton of panels recycled. Economic analysis shows that manufacturing PV modules from recycled materials reduces costs by approximately 60–77% compared to virgin material production, mainly due to avoided energy-intensive upstream processes. From an environmental perspective, the recycling-based pathway yields net benefits across impact categories, as avoided impacts from primary material extraction outweigh additional burdens associated with recycling. Overall, PV recycling in Europe is shown to be environmentally and economically favorable; however, technological maturity and policy constraints remain key barriers to large-scale implementation and a holistic overall recycling process, indicating the need for targeted policy support.

Keywords: photovoltaics recycling; full-recovery-of-end-of-life-panels (FRELP); environmental impact assessment; recycling economics; recycled material value forecasting; secondary material recovery; circular economy

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1. Introduction

With solar photovoltaic (PV) technology playing a key role in facilitating the global energy transition, it has become critical to formulate protocols for effective management of these panels at the end of their service life [1]. Continuous technological breakthrough over the last two decades and the resultant fall in manufacturing costs has enabled large scale deployment of solar PVs to meet climate targets and decarbonization goals. Cumulative installed PV capacity worldwide was reported to have surpassed 2.26 TW by the end of 2024, marking a 29% year-on-year increase with anticipated cumulative installed capacity of 7 TW by 2030 [2,3]. Of this, 95% of the PV market share is held by crystalline silicon (c-Si) technology, with popular models reported to be Aluminum Back Surface Field (Al-BSF), Passivated Emitter and Rear Contacts (PERC) and more recently, the new tunnel oxide passivating contact (TOPCon) model [4].

With the rapid expansion of photovoltaic (PV) deployment worldwide, end-of-life (EoL) module waste is becoming a significant environmental and resource-management concern. Additionally, PV modules contain valuable materials, mainly silver, silicon, copper, aluminum, and solar-grade glass which are often lost through conventional cradle-to-grave management approaches.

From an economic and supply chain perspective, it is estimated that by 2030 alone, the recoverable material value from end-of-life PV panels is projected to reach USD 450 million, including up to 30,000 tons of silicon [5]. It has also been reported that silver alone, despite its relatively low proportion in solar photovoltaic waste, accounts for over 50% of the total economic value of c-Si panels, thereby highlighting the substantial economic benefits associated with recovering not only silver but the maximum possible material from end-of-life panels for reuse [6].

From an environmental standpoint, such recovery of material displaces the need for virgin material extraction and refining. This can substantially reduce energy use, greenhouse gas emissions, and water consumption associated with virgin material production. For instance, it is estimated that production of aluminum from virgin ores requires twenty times more energy than producing recycled aluminum of the same grade and quality [7].

As global PV deployment accelerates and demand for critical materials intensifies, particularly for silver and high-purity silicon, recovering these materials from EoL panels offers a pathway to reduce reliance on primary mining, mitigate supply chain risks, stabilize material costs and ultimately, reduce the environmental burden of the diverted PV waste, virgin material demand and reduction in the associated embodied carbon [8,9].

Many recycling methods exist to achieve this, being broadly classified into mechanical, thermal, chemical and hybrid processes, each differing in complexity, recovery efficiency, and economic viability. The quality and quantity of the recovered material define the economics of the recycling method [6].

Mechanical recycling represents the most established and widely implemented approach, involving dismantling, milling, shredding, and physical separation to recover bulk materials such as aluminum frames, glass, and junction boxes. While this method is cost-effective and industrially scalable, it typically results in downcycling, with limited recovery of high-value materials such as silicon and silver [10].

Thermal processes are often employed to remove the encapsulant material, particularly ethylene vinyl acetate (EVA), which binds the module layers. Techniques such as pyrolysis or controlled heating enable the delamination of glass and silicon wafers; however, they are the most energy-intensive and costliest methods and may lead to material degradation if not carefully controlled [11].

Chemical recycling methods aim to recover high-purity materials through leaching and etching processes, particularly for silicon and precious metals such as silver. These approaches can achieve high recovery efficiencies but often involve hazardous reagents, environmental contaminants, complex processing steps and increased operational costs, limiting their large-scale deployment [10].

To mitigate the limitations of each of the above pathways, hybrid recycling strategies have emerged, combining mechanical, thermal, and chemical treatments to improve material recovery. Among these, the combination of processes that facilitate Full Recovery of End-of-Life Photovoltaic Panels (FRELP) allows maximum recovery of material from EoL PV panels and is thereby in line with circular economy principles [12]. Table 1 lists the state-of-the art FRELP recycling techniques and combinations used.

Table 1. Non-exhaustive list of FRELP recycling methods used worldwide.

Methods	Materials Recovered	Key Information	Source
Thermal + Chemical + Mechanical	Glass 98%, Al 86%, Cu 85–95%, Ag 74–95%	Pyrolysis at 400 °C + HNO_3; mechanical crushing/sieving enhanced metal recovery	[13]
Physical + Chemical	100% metals (67% grade), 76% glass (96% grade)	Ultrasound and thermal pre-treatment separation; mechanical crushing, milling and sieving; heavy medium separation using water, sodium chloride and sodium polythungstate	[14]
Laser + Mechanical	Not specified	Optical laser enabled perfect EVA debonding; mechanical peeling preserved layers	[15]
Mechanical + Thermal + Chemical	Cu 83%, SG-Si 90%, Ag 74%	EVA burned off in a furnace, HNO_3 leaching, HF and NaOH etching	[16]
Thermal + Chemical (Automated)	Glass 94.3%, Al/Cu 100%, Si 72.8%	Automated thermal separation and chemical etching	[17]
Solvent + Thermal + Chemical	Si 86% (99.999% purity)	Toluene immersion; 600 °C burn-off of EVA; HF, H_2SO_4 and HNO_3 etching	[18]
Mechanical + Chemical	Not specified	Milling, sieving, H_2SO_4 etching	[19]
Thermal + Chemical	>99.0% Ag, >98.0% Si, Cu, Pb, Sn, Al, glass	Pyrolysis + molten salt etching	[4]
Thermal + Chemical	Overall, 76.4% of the cells were recovered	Pyrolysis + etching	[11]
Chemical + Ultrasonic radiation	EVA removed, but cells sustain cracks	Ultrasonic radiation with immersion in chemical solvents to remove EVA	[20]

Germany, although not the world's largest solar PV market today, was an early leader in large-scale deployment of crystalline silicon (c-Si) modules beginning in the late 1990s [21]. As a result, it is now among the first countries to confront the substantial end-of-life (EoL) challenges associated with aging PV installations. This makes Germany an appropriate and timely focal point for the present study. Various recycling approaches have been implemented in the country, as indicated in Table 2, with a few attempts by recyclers like LuxChemtech at FRELP methods.

Despite growing recognition of the importance of photovoltaic recycling, existing studies remain fragmented, often assessing environmental impacts and economic feasibility in isolation and primarily focusing on low-recovery or single-stage processes. Further, relatively fewer studies integrate techno-commercial and environmental dimensions within a closed loop manufacturing perspective.

Recent economic and techno-economic studies have highlighted both the opportunities and uncertainties associated with advanced PV recycling. Chowdhury et al. [23] combined life cycle assessment (LCA) and life cycle costing (LCC) to evaluate laser-based recycling pathways for PV modules, concluding that advanced recycling routes can substantially reduce environmental burdens relative to landfill disposal or low-recovery recycling. A techno-economic assessment by Granata et al. found that the profitability of an FRELP pathway involving pyrolysis, chemical leaching, and sieving is strongly influenced by silver recovery rates, energy consumption, and plant scale [24]. Similarly, Dias et al. used a combined LCA–LCC, scenario-based approach to compare several end-of-life recycling options for PV modules using shredding and electrostatic separation in Brazil, showing that FRELP is attractive from an environmental standpoint, but not so economically unless the market conditions, waste volumes and necessary infrastructure are present [25].

Table 2. The few recycling techniques practiced in Germany as of 2025 [22].

Recyclers in Germany	Technology	Material Recovered	Comment
Reiling	Mechanical recycling results in downcycling due to contamination.	Cables, Frame, Junction boxes, Ferrous metals, Non-ferrous metals, Polymers/foils, Glass cullet, Mixture of glass cullet, foil and metals, Dust, Other (waste, emissions)	None of the valuable materials are recovered intact except glass and aluminum frame.
Lux Chemtech	High-pressure water jets remove materials from glass; silver is acid-recovered and electrolyzed, while a light-pulse process (like Flaxres) was under construction in 2022.	Cables, Frame, Junction boxes, Ferrous metals, Non-ferrous metals, Copper, Silicon, Other semiconductors, Polymers/foils, Dust, Other (waste, emissions)	Copper, Aluminum, Silicon, Silver and Glass are recovered. However, chemicals used are toxic, causing secondary pollution.
Flaxres	Light-pulse delaminates modules; third parties recover silver/silicon from solar cell, manufacturers reuse aluminum/copper. Mobile units allow on-site dismantling and direct glass transport.	Cables, Junction box, Solar cell, Frame, Glass, Encapsulant	Encapsulants in PV modules can be easily peeled off from module. Energy consumption is less, because its process limits up to delamination only.

At a systems level, dynamic material flow and resource forecasting studies have emphasized the strategic importance of PV recycling for future critical material supply. Song et al. used Weibull forecasting to model long-term PV waste generation and secondary resource recovery potential in China, demonstrating the substantial future availability of recoverable silicon, silver, aluminum, and copper from end-of-life modules [26]. Likewise, Cucchiella et al. highlighted the economic value embedded within PV waste streams and identified recycling as a potentially important secondary raw material source in Europe [27].

Process-related work such as Mahmoudi et al., for instance, investigated pyrolysis combined with molten salt treatment and demonstrated high recovery efficiencies for silicon and silver, but the process relied on elevated temperatures and chemical treatment stages associated with substantial energy demand [28]. Likewise, Azeumo et al. observed that mechanical and chemical treatment can damage silicon wafers and contaminate recovered fractions, reducing recovered material quality despite high overall recovery rates [14]. Few studies have adopted newer and more advanced processes like lasers and ultrasonic separation in combination with chemical techniques. But these studies report damage to the solar cell, thereby affecting the quality of the material recovered [20,29].

Although these studies provide valuable contributions individually, they share three key limitations: they rarely integrate environmental and economic assessment in a single, harmonized framework; they seldom model full closed-loop c-Si module remanufacturing using recovered materials; and the FRELP pathways analyzed are often limited to combinations of mechanical methods, pyrolysis and chemical methods like acid leaching or using organic solvents, all of which either pose environmental risks or yield substandard quality of recycled material. Limited attention has been given to hybrid recycling configurations integrating non-destructive delamination and selective purification techniques capable of supporting high-purity material recovery.

By explicitly addressing these gaps, the present study positions itself as a bridge between process innovation, macro-level waste and resource projections and region-specific circular manufacturing analysis. To address this gap, this study proposes a novel adaptation of the Full Recovery of End-of-Life Photovoltaics (FRELP) pathway, incorporating light-

pulse delamination in combination with molten salt etching for material separation and purification. While both techniques have been explored individually in prior research, their combined application within a full recovery process has not been previously assessed from either an environmental or economic perspective.

Using Germany as the case study, this work aims to quantify the economic and environmental benefits of applying the proposed FRELP-based recycling approach to end-of-life (EoL) crystalline silicon PV modules and using the recovered material, mainly copper, silicon, glass, aluminum and silver, to manufacture new PV panels. The specific objectives and scope of this study are as follows:

- Estimate the economic value of valuable materials such as silicon, copper, glass, aluminum and silver recovered from EoL solar PV panels.
- Prepare and compare the cost estimates for manufacturing PV panels in Germany using virgin materials versus recycled material recovered from EoL PV panels.
- Compare the environmental impact of manufacturing PV panels from virgin material versus the pathway wherein virgin material is substituted by recycled material recovered from EoL panels.

The scope of this study focuses on crystalline silicon photovoltaic modules, which dominate the global market, particularly Al-BSF and PERC, and considers end-of-life treatment within a German/EU context characterized by a high share of low-carbon energy in the national grid, high labor costs, stringent environmental regulations and increasing demand for circular resource strategies.

It is worth noting that this study is subject to several limitations that should be acknowledged when interpreting the results:

- Reliance on secondary data and several assumptions: All process parameters, and cost assumptions are derived from the existing literature and publicly available sources rather than primary experimental or industrial-scale data. The environmental impact assessment in particular relies heavily on literature-reported inventories, regional variability in indicators and uncertainty associated with scaling pilot-scale recycling data to industrial contexts. The economic findings on the other hand rely on several process and market-related assumptions and should therefore be interpreted as part of a conceptual techno-economic assessment and should be regarded as indicative scenario-based estimates rather than definitive industrial-scale outcomes.
- Lack of empirical validation: The proposed integration of light-pulse delamination and molten salt etching has not yet been validated at industrial scale. The analysis therefore relies on pilot-scale studies, laboratory test data, and scale-up assumptions that may not fully capture practical technical or economic challenges.
- Data variability and uncertainty: Variations in system boundaries, methodologies, and reported efficiencies across literature sources introduce uncertainty into the assessment. Additional assumptions were also required where reliable public data were unavailable, limiting the generalizability of the results.
- Future technological development: The present study focuses specifically on Al-BSF and PERC crystalline silicon PV modules. Consequently, the findings may not fully represent future PV waste streams, which are expected to increasingly include emerging technologies such as TOPCon, heterojunction, tandem, bifacial, and glass–glass modules. Changes in module architecture, material composition, and silver consumption may influence future recovery efficiencies, recovered material values, and recycling economics. Therefore, the results should be interpreted within the technological scope and assumptions adopted in this study.

2. Materials and Methods

This study applies a mix of analytical and desk-based methods (Figure 1) to comprehensively examine the chosen recycling pathway of end-of-life (EoL) solar photovoltaic (PV) panels. At the heart of the research lies a comprehensive literature review, which forms the foundation for all subsequent methods. The approach combined literature review with modeling and economic and environmental assessment to evaluate the system-level dynamics of PV circularity in Germany.

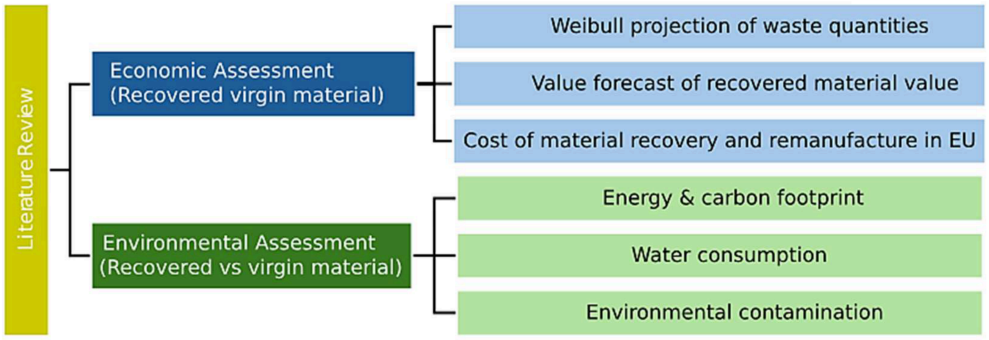


Figure 1. Overview of methodology deployed.

2.1. FRELP Pathway Considered in This Study

The FRELP pathway examined in this study is illustrated in Figure 2 and entails the following steps.

- The PV panels first undergo disassembly to remove the junction box and cables.
- The panel is put through the light-pulse delaminator which exposes the panel to short pulses of light. The light travels through the glass and encapsulant (EVA) layer and heats up the panel in a fraction of a second. Thermal build-up of the boundary layers results in the separation of the module into glass, Al frame, EVA (intact), backsheet and Si solar cell [30].
- The solar cell undergoes salt etching, whereby it is immersed in a molten salt mixture of NaOH-KOH at a temperature of 200 °C. Once heated, the cells are then rapidly cooled in water, allowing the collection of metallic silver without the need for acids, conversion processes, or electroplating. Along with silver, copper ribbons and lead/tin solders are also separated and collected via oxidation, reduction and electrodeposition. Following this, a NaOH alkaline leaching step is applied at 55 °C to remove aluminum embedded within the solar cells, leaving behind 99.99% pure silicon [4].
- Silicon then undergoes further purification to solar grade via zone refining.
- The recovered silver, copper and aluminum undergo further purification if necessary.

The energy required to process 1 ton of solar PV waste using the proposed FRELP recycling method is provided in Table 3, subject to the limitations outlined therein.

The combination of light pulse and molten salt etching was selected since this pathway offers the following benefits:

- It is non-destructive and preserves the integrity of recovered components, even EVA [32].
- These two steps account for very low emissions as minimal energy is consumed [4].
- Salt etching uses non-hazardous chemicals, thereby reducing pollution risks [4].

Further, this process also offers a qualitative assessment of the comparative advantage of the proposed FRELP method (Table 4) compared to the existing techniques summarized in Table 1.

The comparative assessment in Table 4 indicates that the proposed FRELP pathway appears to address several key limitations commonly associated with existing PV recycling approaches, particularly those related to thermal energy demand, solvent use, oxidative chemical emissions, and mechanical damage to high-value materials. Collectively, these characteristics suggest that the proposed FRELP configuration may offer strong potential for environmentally favorable and high-purity PV recycling.

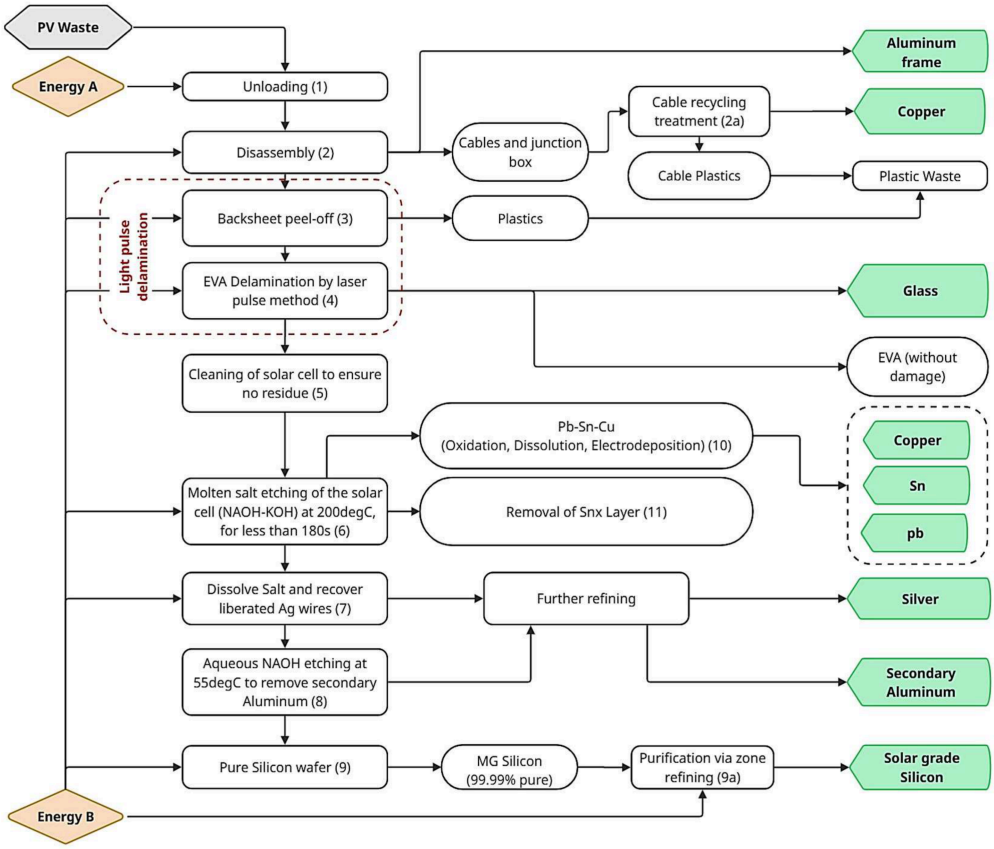


Figure 2. FRELP recycling pathway considered in this study (Adapted based on [4,31]).

Table 3. Energy needed for the FRELP recycling for 1 ton of PV panel [4,22,31].

Energy Flow	Step	Process	Energy Type [1]	Unit	Value
Energy A (Input)	1	Unloading (1)	Diesel fuel	L	1.14
Energy B (Input)	2, 2a	Disassembly of cable, junction box and Aluminum frame (2), Cable recycling treatment (2a)	Electricity	kWh	50
	3	Backsheet peel off (3)	Electricity	kWh	
	4	Laser pulse methodology: Glass separation (EVA delamination) (4)	Electricity	kWh	
	5	Cleaning of removed solar cell	Electricity	kWh	
	7, 8, 9, 10, 11	Molten salt etching and aqueous salt etching, removal of secondary Aluminum, Pb, Sn, Cu	Electricity	kWh	25.8
	9a	MG-Si to SG-Si (9a)	Electricity	kWh	63.4

[1] Energy required for further processing of copper, aluminum, glass for solar grade is not accounted.

Table 4. Qualitative comparative advantage of the proposed FRELP pathway compared to those listed in Table 1.

Recycling Pathway	Aspect	Limitations Reported in the Literature	Proposed FRELP Pathway (Light Pulse + Salt Etching)
Thermal + Chemical + Mechanical (Pyrolysis + HNO_3 + Crushing and sieving) [13]	Energy use	High energy demand due to sustained heating at ~400 °C. Latunussa et al. reported energy needs of about 2780 MJ per tonne of PV waste processed, with thermal treatment representing a major contributor to the demand [11].	Omits thermal treatment. From Appendix B.2. of this study, the collective energy demand of light-pulse separation, salt etching, electrodeposition and zone refining come to around 147.65 kWh per tonne PV, which is around 532 MJ per tonne of PV.
	Environmental impact	Pyrolysis emissions; HNO_3 has strong oxidizing potential and therefore can generate NOx gases and waste streams containing nitrates that can cause eutrophication [33].	Lower oxidation potential of KOH-NaOH yields little to no NOx. Resulting waste is composed of saline-alkaline effluents which can be easily treated [4].
	Material quality/purity	Mechanical crushing may damage wafers and contaminate recovered materials resulting in substandard purity of recovered material, especially high value material like silver, copper and silicon [10].	Non-destructive delamination better preserves material integrity and supports high-purity recovery suitable for remanufacturing. Even the EVA layer is recovered intact [4,32].
Physical + Chemical (Ultrasound + Thermal + Mechanical + Heavy Medium Separation) [14]	Environmental impact	Use of organic solvents such as toluene and xylene introduces volatile organic compound (VOC) emissions and solvent recovery requirements [14].	Reduced dependence on organic solvents, potentially lowering VOC emissions [4].
	Material quality/purity	Mechanical shredding and milling can damage silicon wafers and contaminate recovered fractions. Although 100% metal recovery was achieved, the recovered metal fraction had only ~67% grade due to contamination by glass and EVA residues. Glass recovery was limited to 76% [14].	Non-destructive nature of the method enables material to be recovered intact, which can undergo further purification to achieve solar grade [4,30].
Thermal + Chemical (Automated) [17]	Energy use	Thermal separation remains energy-intensive despite process automation. The associated emissions are also a concern [17].	Much lower energy intensity as demonstrated in Appendix B.2.
	Material quality/purity	Though high recovery efficiency was reported (94.3% glass, 100% Al/Cu), Silicon recovery remains at 72.8% highlighting the degrading nature of the combined thermal and chemical steps [17].	Recovery efficiencies are much higher due to non-destructive delamination, targeted salt etching and downstream purification [4,30].
Chemical + Ultrasonic Radiation [20]	Environmental impact	Relies on organic solvents including toluene, benzene, trichloroethylene (TCE) and o-dichlorobenzene (O-DCB), which introduce VOC emissions, solvent recovery requirements and hazardous liquid waste streams [20].	No such risks due to non-dependence on organic solvents [4,30].
	Material quality/purity	Complete EVA dissolution was achieved; however, PV cell cracking and swelling were observed in several solvents, particularly toluene [20].	The proposed process is intended to minimize mechanical stress during separation, thereby improving preservation of silicon wafers and material integrity [4,30].

2.2. EoL Waste Quantification Using Weibull Forecasting

Cumulative annual PV panel waste was modeled using the Weibull cumulative distribution (Equation (1)) function below, to predict the volume of EoL anticipated until 2045 [34]. The model assumes that the majority of the failures occur closer to the end-of-life of the panel with no premature or early failures. For enhanced resolution, the modeling will consider three different life spans, one being optimistic at 30 years, second being a more realistic lifespan at 25 years and a pessimistic scenario at 20 years. Weibull parameters used in the model are presented in Table 5. The resulting estimates were compared with existing findings in the scientific literature to validate the projections.

$$F(t) = 1 - e^{\left(-\left(\frac{t-y}{T}\right)^{\alpha}\right)} \quad (1)$$

Table 5. Weibull parameters used for modeling waste throughput.

Case	Weibull Parameters		Citation
	Shape Factor (α)	Scale Factor (T)	
Optimistic (S1)	5.3759	30	[34,35]
Baseline (S2)	5.3759	25	
Pessimistic (S3)	5.3759	20	

Full step-by-step calculations to estimate the waste throughput are in Appendix A.

2.3. Value Forecast of Recovered Material

This study forecasts the value of silicon, silver, copper, aluminum and glass between 2025 and 2045 by applying their respective compound annual growth rates (CAGRs) with appropriate assumptions as outlined in Table 6. The CAGR values for these materials are not officially reported for the period between 2033 and 2045 and are, therefore, assumed to be at 1% for this study. To add further rigor, a sensitivity analysis has also been carried out for each of the materials for CAGR values of 0% and 2%.

Table 6. Compound annual growth rates used to estimate the value of the recovered material.

Material	CAGR (2025 to 2032)		CAGR (2033 to 2045)		
	CAGR	Source	CAGR	CAGR (Sensitivity Study)	Source
Glass	5.45%	[36]	1%	0%, 2%	Assumption
Aluminum	4.83%	[37]	1%	0%, 2%	Assumption
Silicon	4.20%	[38]	1%	0%, 2%	Assumption
Silver	4.10%	[39]	1%	0%, 2%	Assumption
Copper	6.5%	[40]	1%	0%, 2%	Assumption

The value forecast of these materials, based on the waste quantities derived using the Weibull function and the aforementioned CAGR values, was estimated using the following Equation (2):

$$P_F = P_P \times (1 + CAGR)^n \quad (2)$$

where

P_F is the future price of the material to be estimated;
P_P is the baseline or current price of the material;
CAGR is the compound annual growth rate;
n is the number of years past the baseline or current year.

The baseline price (P_p) of each material used in this study is given in Table 7. These values of CAGR and P_p are applied to all three scenarios S1 (EoL at 30 years), S2 (EoL at 25 years) and S3 (EoL at 20 years).

Table 7. Unit prices of the recovered materials used in this study.

Material	P_p (€/kg) as of 2 October 2025	Source and Notes
Glass	0.0801	P_p value is sourced from Business Analytiq [41]. Glass recovered is assumed to be contaminated and needing purification. A 10% depreciation applied based on suggestion by Alfred University [42]
Aluminum	1.80	P_p value is sourced from EU Recycle [43]. Secondary aluminum with quality close to that of primary aluminum ($2646/ton reported for primary silicon; 20% discount applied, based on Sigworth [44].
Silicon	5.83	P_p value is sourced from Bernreuter Research [45]. Solar grade silicon is recovered. No depreciation.
Silver	1104.021	P_p value is sourced from Live Price of Gold [46]. Silver recovered using proposed method is 99.57% pure [4]; depreciation is already accounted for in the rate.
Copper	8.44	P_p value is sourced from Westmetall [47]. Material recovered from suggested method is typically 99.9% pure [48]. Therefore, no depreciation.

2.4. Cost Estimates for Material Recovery

Cost estimates were built for the recovery of the most valuable material from the EoL panels, namely, silicon, silver, copper, aluminum and glass, using the FRELP method described in Figure 2. Several sources of the literature were consulted to identify the quantities of each of these materials recovered from EoL waste (Table 8). Comparing all four studies, it is evident that glass and copper quantities per ton of PV waste increased from the older studies to the newer studies, whereas in contrast, a fall in the quantities of aluminum, silicon and silver is observed. This reflects the evolution in the design of c-Si panels over the years, from Al-BSF to TOPCon [49]. For the purpose of this study, the material composition reported by Markert et al. was utilized as it is representative of the composition of the formerly popular Al-BSF panel, the installations of which are anticipated to reach end-of-life earlier than PERC or TOPCon [1].

Table 8. Quantities of various PV components in tons recovered from 1 ton of EoL waste, as reported in the existing literature.

Material Description	Material Composition (with Sources)			
	[28] (t Per 1 t of PV Waste)	[1] (t Per 1 t of PV Waste)	[31] (t Per 1 t of PV Waste)	[50] (t Per 1 t of PV Waste)
Glass	0.700000	0.68600	0.68707	0.75360
Aluminum	0.185000	0.18265	0.10300	0.10300
Silicon	0.036500	0.03468	0.03100	0.00640
Silver	0.000530	0.00050	0.00009	0.00007
Copper	0.004610	0.00438	0.01500	0.00940
Tin	0.000265	Not reported	0.00038	Not reported
Lead	0.000265	Not reported	0.00067	Not reported

The costs incurred to recover these materials through recycling are broken down as shown in Table 9. A hypothetical plant assuming a medium-sized capacity to handle 4000 tons per year. The detailed calculation methodology is provided in Appendix B.

Table 9. Cost types considered for recovering panels using the proposed recovery method.

Cost Type	Cost Estimate Method	Location of Methodology Details
CAPEX	CAPEX for salt etching taken from the existing literature for the facility and the equipment for light-pulse delamination, salt etching, zone refining.	Appendix B, Appendix B.1
Electricity costs	Only electrical energy costs are involved. Electricity consumption is estimated based on the existing literature and the associated costs are calculated based on the electricity tariff in Germany.	Appendix B, Appendix B.2
Transportation	Assuming a one-way transport distance of approximately 1100 km, the transportation costs cover fuel and driver expenses, vehicle ownership costs, maintenance/repair and tolls/vignettes, all estimated based on appropriate assumptions and values from the existing literature.	Appendix B, Appendix B.3
Chemicals	Costs of the chemicals used per ton of PV waste. Wholesale prices were applied.	Appendix B, Appendix B.4
Labor and other OPEX	Labor estimates were built for a medium-sized plant using staff rates and full-time-equivalent (FTE) shifts typically practiced in Germany. Cost of Personal Protective Equipment (PPE), insurance, maintenance and other OPEX are assumed to be a 30% add-on to the labor expenses.	Appendix B, Appendix B.5

2.5. Cost Estimates for Remanufacture of PV Panels with Recovered Recycled Material

The cost for remanufacturing PV panels using material recovered from one ton of EoL PV waste using the recycling method outlined in this study was estimated in Euro per Watts-Peak (€/Wp) using the methodology outlined in Table 10. The case of manufacturing a PERC PV panel is considered as PERC is widely in use in today's market compared to the formerly popular Al-BSF.

Table 10. Methodology used to estimate the cost to manufacture solar PV from recycled material.

Step	Description	Data Source	Notes
1	Determine the quantities of Al, Si, Cu, Ag and glass from 1 t of PV waste.	[1]	Already pre-estimated in source literature
2	Determine the quantity (in kg/Wp) of the following material needed to manufacture 1 Wp of PERC PV:	-	-
	Glass	[49]	Already pre-estimated in source literature
	Aluminum	[49]	
	Silicon	[21]	
	Silver	[51]	
	Copper	[52]	
	Lead	[53]	Already pre-estimated in source literature. Virgin material added as it is not recovered by recycling.
	Tin	[53]	
	EVA	[53]	
	Backsheet	[53]	
3	Determine how many WP of solar PV can be manufactured using each material from step 1.	Own calculation	$W_P possible = \frac{Qty\ recovered(Step1)}{Qty\ needed(Step2)}$ This is done for each recovered material separately. This is not applied to lead, tin and EVA. The resultant value is in Wp.

Table 10. *Cont.*

Step	Description	Data Source	Notes
4	Setting 15 kWp as a target, determine how much recovered material from 1 t of PV waste will be used up, which ones are in excess and which ones are deficit.	Own calculation	This step is done to determine benefits from leftover material and expenses for deficit material needed to manufacture 15 kWp of solar PV. Formula used: Material left or needed (in W_p) $= 15,000 - W_p$ from Step 3
5	Material quantities obtained in Wp in Step 4 are converted to kg.	Own calculation	This step to convert the quantities from Step 4 from Wp to kg is needed in order to determine the cost savings or expenses associated with the leftover or deficit material. Formula used: $Qty(kg) = Qty(Step\ 4) \times Qty(Step2)$
6	Determine cost savings or expenses using quantities from Step 5, multiplied by the unit rates (from Table 6) of the below material:	-	-
	Glass	Table 6	These materials are recovered from recycling. Virgin material would be used only in case of deficiencies.
	Aluminum	Table 6	
	Silicon	Table 6	
	Silver	Table 6	
	Copper	Table 6	
	Lead	[54]	These materials are not recovered through the proposed recycling method and therefore, virgin material is assumed to be used for the remanufacturing of the PERC panel.
	Tin	[55]	
	EVA	[56]	
	Backsheet	[57]	
7	Additional costs, aside from material costs, are to be included, such as:	-	-
	Cost of material recovery through recycling		Estimated using methodology outlined in Section 2.4.
	Additional purity costs	Assumed to be 25% of the value of the recovered material per tonne of PV waste (Table 14) add-on top	This is a contingency cost added on top for any additional purification process necessary to deem the recycled material pure enough for PV manufacture. Due to lack of reliable evidence in the existing literature for the fraction of costs amounting to such purification costs, a crude assumption of 25% of the recovered material value from Table 14 was added on top as a conservative estimate.
	Silicon ingot/wafer manufacture	[58]	The process of recycling would allow evasion of the Siemen's process and polysilicon chunk formation. However, the recovered material would still need to undergo the phases of ingot/wafer production and therefore, the associated costs are accounted for.
	Solar cell manufacture	[58]	Ingot/wafer manufacture is followed by solar cell manufacture.
	Module Assembly	[58]	Solar cell manufacture is followed by module assembly.
8	Summation of all of the above	Authors' own calculation	This represents the total costs of manufacturing a typical PERC panel using material recovered from the FRELP recycling method defined in this study.

The resulting cost estimate was then compared with the cost (in €/Wp) of manufacture of a brand-new PERC solar PV in Europe.

2.6. Environmental Impact: Recycling Versus Using Virgin Material

The environmental performance of the proposed FRELP-based recycling pathway was quantified using a comparative life cycle assessment and benchmarked against a functionally equivalent virgin-material-based PV manufacturing pathway. Table 11 summarizes the key process stages of the virgin and recycling-based manufacturing pathways. While downstream PV cell manufacturing is identical for both routes, the two pathways differ fundamentally in feedstock origin, material extraction and purification processes, which form the basis of this comparative environmental assessment.

Table 11. Differences and commonalities between the recycling-based and virgin material-based manufacturing pathways.

Process Stage	Virgin Material-Based Pathway	Recycling-Based Pathway	Commonality/Difference
Raw material source	Primary raw materials (quartz, metal ores, bauxite)	EoL c-Si PV modules	Difference
Initial material preparation	Investigation of mining sites	Disassembly of PV modules (frame, junction box, glass) and light-pulse delamination	Difference
Silicon extraction	Quartz reduction followed by chemical purification	Molten salt etching to liberate silicon cells	Difference
Silicon purification	Siemens process and related refining routes	Zone refining of recovered silicon	Difference
Silver recovery	Mining and refining	Salt etching followed by hydrometallurgical recovery	Difference
Copper recovery	Mining and conventional smelting	Oxidation–dissolution followed by electrodeposition	Difference
Aluminum supply	Bauxite mining and refining	Direct recovery from frames and cell components	Difference
Solar glass supply	Primary float glass production	Recovery and cleaning of solar glass	Difference
Energy inputs	High energy demand for extraction and refining	Energy demand for delamination, etching, and purification	Difference
Chemical inputs	Acids, reductants, and process chemicals	Molten salts, acids, and electrolytes	Difference (assumed)
Water consumption	All raw material extraction and refining processes	Salt etching, electrodeposition and zone refining	Difference
Output material quality	Market-grade materials for PV manufacturing	Assumed equivalent PV-grade materials	Commonality (assumed)
Downstream manufacture	Ingot, wafer, cell processing, module assembly	Identical downstream processing	Commonality

The assessment relies entirely on pre-existing life-cycle inventory (LCI) and impact assessment results from peer-reviewed literature and technical reports, rather than on primary process measurements or simulations. For a functional unit of 1 ton of PV panels, comparative environmental impact results from existing studies are presented side-by-side to quantify net environmental benefits and trade-offs. The parameters analyzed are indicated in Figure 3 as suggested by the European Commission [59].

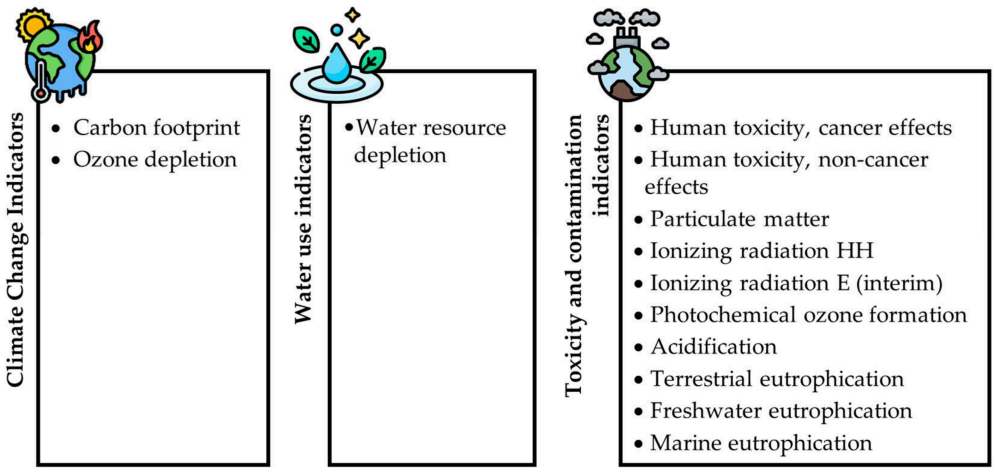


Figure 3. Environmental indicators used in this study [59].

The novelty of this work lies in the construction of a unified, indicator-level comparison between virgin- and recycled-material-based PV manufacturing using an advanced FRELP

pathway that differs from previously assessed recycling configurations. While prior studies have quantified impacts of virgin production and recycling separately, this study provides a harmonized comparative synthesis that explicitly evaluates material substitution effects and highlights the environmental performance of high-purity recycling routes relevant to next-generation PV circularity.

Limitations of the approach include reliance on literature-reported inventories, regional variability in indicators and uncertainty associated with scaling pilot-scale recycling data to industrial contexts.

3. Results and Discussion

3.1. EoL Waste Quantification

Figure 4 showcases the predicted quantity of PV waste accumulated for the optimistic (S1), baseline (S2) and pessimistic (S3) cases as outlined in Section 2.2.

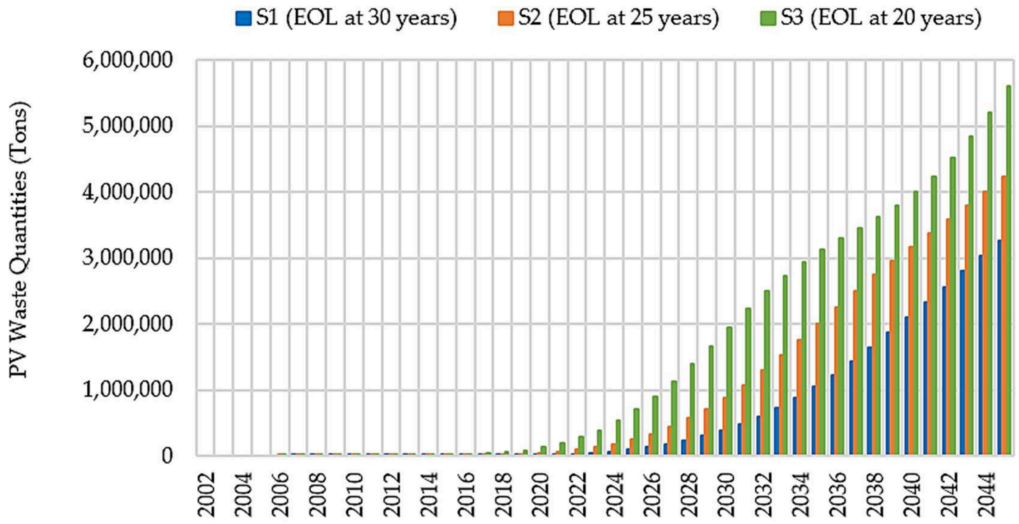


Figure 4. Waste throughput projection for three different panel lifetimes.

The projections indicate that, across all three scenarios, the accumulation of end-of-life PV waste begins between 2022 and 2026 and increases steadily thereafter. This period represents a critical window for the timely development and scaling of adequate recycling infrastructure to manage the anticipated surge in waste volumes from the aging first-generation installations. By 2045, the cumulative waste mass is estimated to reach 3.3 million tons under Scenario 1 (S1), 4.2 million tons under Scenario 2 (S2), and 5.6 million tons under Scenario 3 (S3). The divergence between scenarios highlights the sensitivity of waste generation to deployment trajectories, system lifetimes, and repowering rates. Higher cumulative waste volumes under Scenarios 2 and 3 suggest that accelerated PV deployment, shorter operational lifetimes, or increased early replacement rates could substantially intensify recycling demand.

The projected waste volumes suggest that existing recycling capacity, largely based on mechanical processes, may be insufficient to manage forthcoming waste flows, risking stockpiling, landfilling and suboptimal material recovery. At the same time, these waste streams constitute a significant secondary resource of silicon, aluminum, copper, silver, and solar glass, and failure to recover them would increase dependence on virgin material extraction, with associated environmental and supply-chain impacts.

Table 12 provides a comparison of the resulting throughput estimates for Germany with those in the existing literature. The estimates for the regular loss scenario are quite close, especially compared to those of IEA PVPS [2].

Table 12. Verification of estimated throughput volume for Germany with the existing literature.

Data Source	Year Projected for	Regular Loss (EoL at 30 Years; in Million Tons)
[5]	2050	4.30
[2]	2045	3.42
This report	2045	3.30

3.2. Value Forecast of Recovered Material

Using the unit rates of silicon, copper, silver, glass and aluminum given in Table 6 of Section 2.3, the value of these materials embedded in 1 t of PV waste is estimated to be €11,74.88 as indicated in Table 13.

Table 13. Current value of material recovered from one ton of PV waste.

Material Description	Qty (kg) Recovered Per Ton of Panels [1]	Unit Value from Table 6 (EUR/kg)	€/Ton of Panel
Glass	686.00	0.0801	54.95
Aluminum	182.65	1.8	328.77
Silicon	34.68	5.83	202.18
Silver	0.50	1104.021	552.01
Copper	4.38	8.44	36.97
		Total (€/ton of waste)	1174.88

The value of these materials, when projected using the compound annual growth rate (CAGR) values from Table 5 of Section 2.3 for S1, S2 and S3 between the years 2025 to 2045, yields the annual aggregated value projections indicated in Figure 5.

Figure 5 illustrates that silver, despite constituting the smallest mass fraction of a PV module, contributes the highest recovery value, followed by aluminum and silicon. In 2045, the aggregated value of recovered silver across the three scenarios is estimated to range between €200,000 and €340,000, reflecting differences in recovered mass. The corresponding cumulative value ranges for aluminum and silicon are €120,000–€208,000 and €67,000–€115,000, respectively. Scenarios 2 and 3 exhibit a decline in recovered material value between 2035 and 2045, attributable to the reduction in material mass recovered projected by the Weibull-based waste generation model.

Since the above projections assume a flat 1% CAGR during the period for which published market forecasts are unavailable (2033–2045), an additional sensitivity analysis was conducted using alternative CAGR assumptions of 0% and 2% for the same period, as shown in Figure 6. To avoid compounding uncertainty across both waste generation and market valuation parameters, the sensitivity analysis was applied exclusively to the baseline waste projection scenario (S2), while Scenarios S1 and S3 were retained solely for projection of PV waste generation volumes.

Under the sensitivity cases of CAGR 0% and 2%, the value of silver, aluminum and silicon recovered by mass in 2045 ranges between €180,000 and 230,000, €110,000 and 141,00 and €60,000 and 80,000 respectively. The analysis indicated that although absolute recovered material values varied across scenarios, the overall economic benefits of recycling remained unchanged.

Similarly, the variation of the unit rates of these materials between 2025 and 2045 is captured in Figure 7, subject to the limits of the assumptions outlined in this study in Table 5 of Section 2.3. These unit rates have also been projected for CAGR values of 0%, 1% and 2%.

3.3. Cost to Manufacture PV Modules with Recovered Recycled Material

Using the method outlined in Section 2.5, the cost of manufacturing PERC PV panels in 2025 using silicon, silver, copper, aluminum and glass recovered from 1 t of PV waste is provided in Table 15. This study sets a target to manufacture 15 kWp of PV and identifies

how much of the recovered material from one ton of waste is sufficient to meet this target, which materials are in excess and which ones are in deficit, thereby needing virgin or addition recovered material. It is worth noting that other essential material needed for PV manufacture such as the solders, backsheet and encapsulant are not recovered through the proposed recycling method and would have to rely on virgin material.

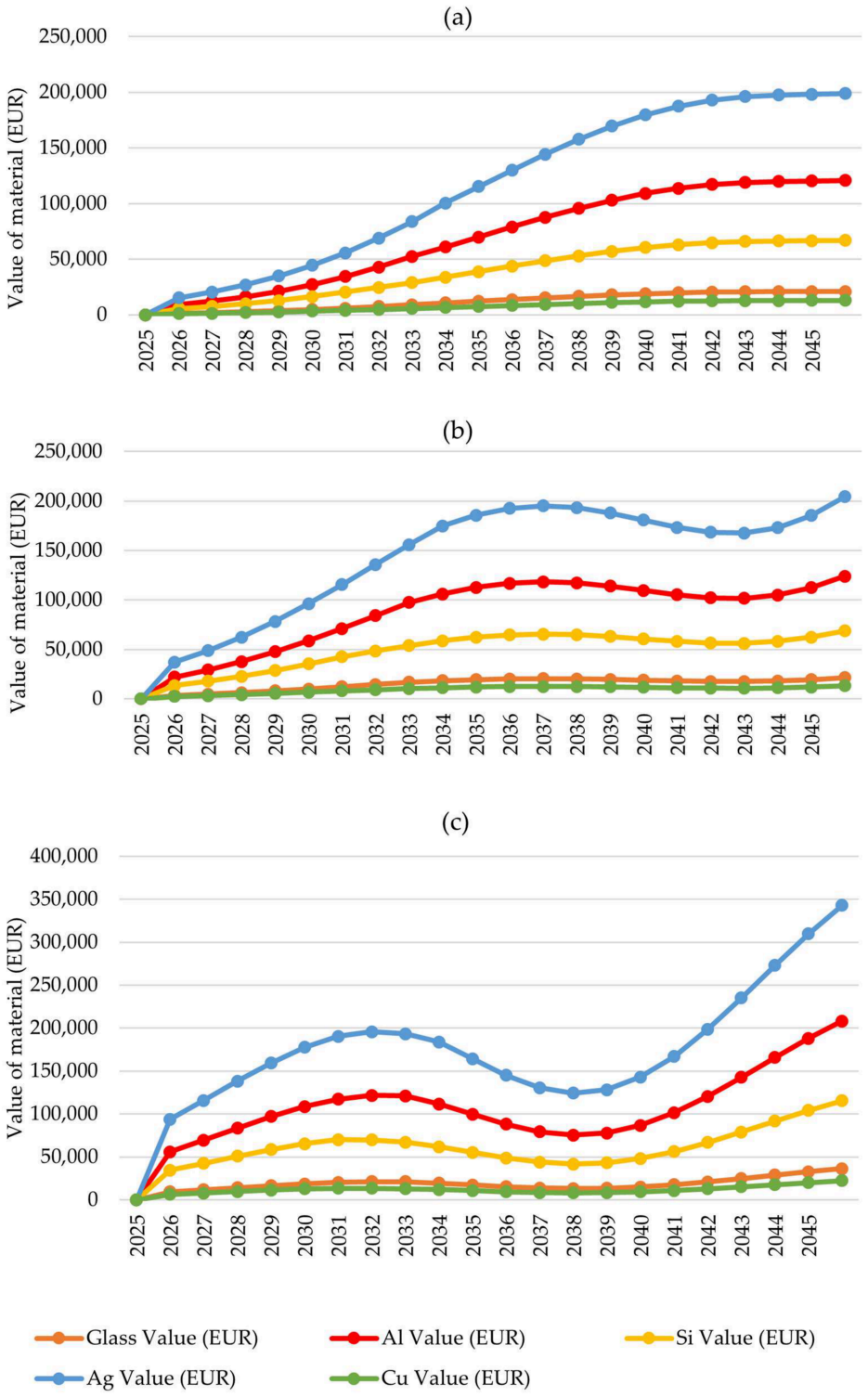


Figure 5. Annual aggregated mass-based value of recovered material between 2025 and 2045: (**a**) for Scenario 1 (EoL at 30 years); (**b**) for Scenario 2 (EoL at 25 years); (**c**) for Scenario 3 (EoL at 20 years).

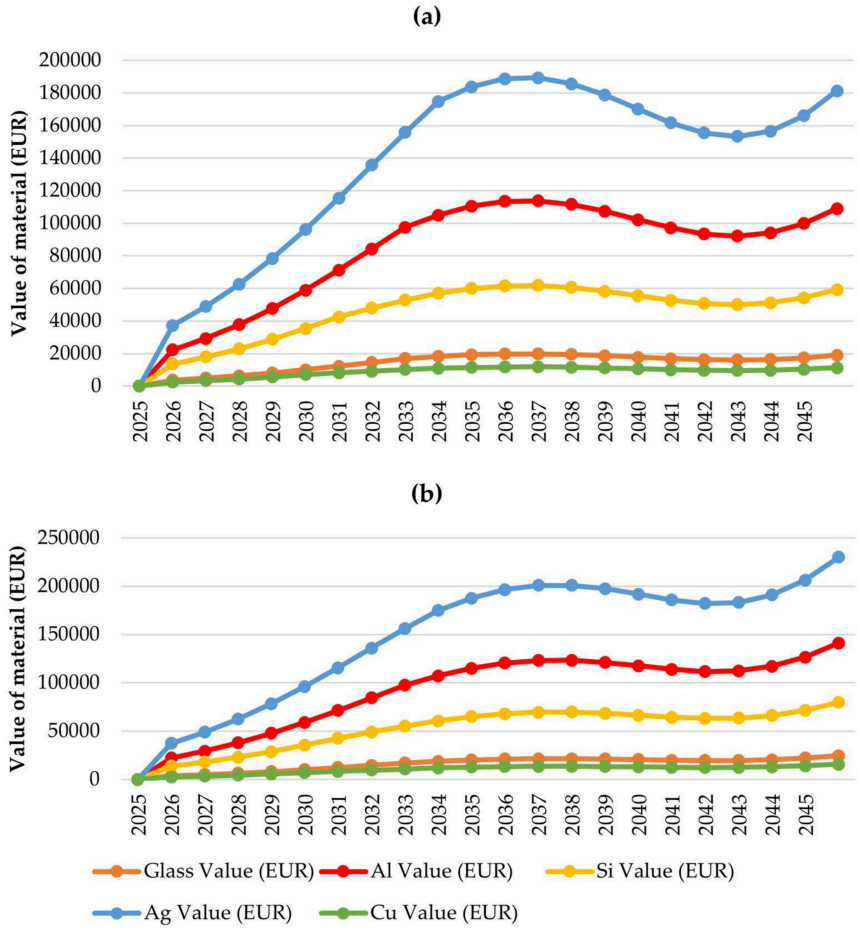


Figure 6. Sensitivity analysis of recovered material value in Scenario 2 for the following values of CAGR for the period where market forecasts are not available: (**a**) CAGR of 0%; (**b**) CAGR of 2%.

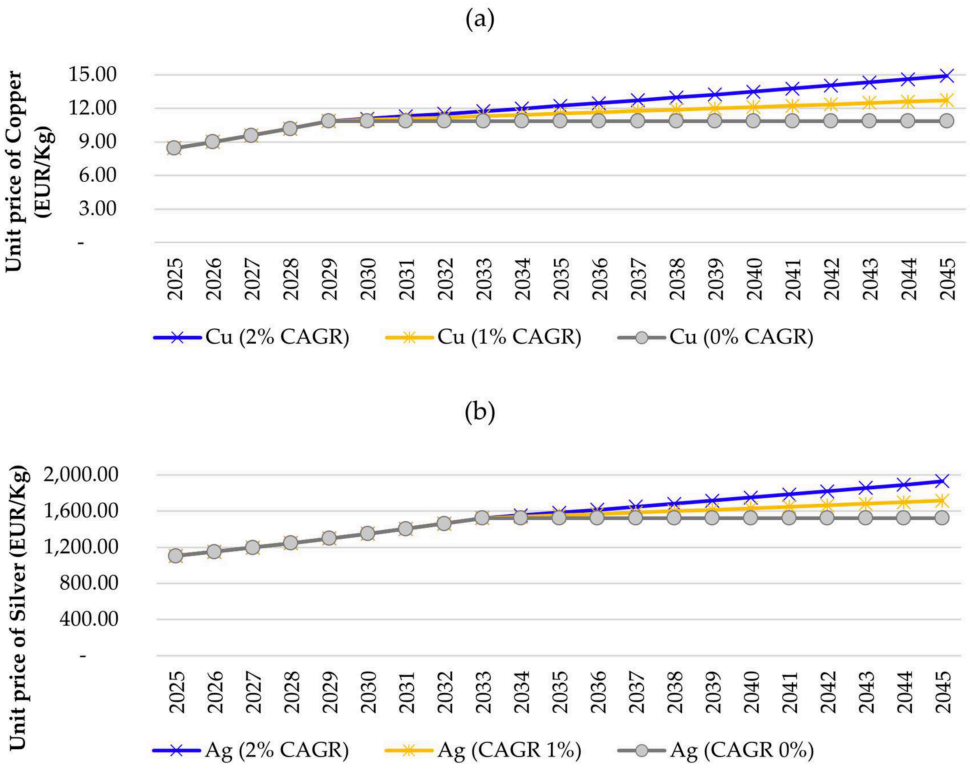


Figure 7. *Cont.*

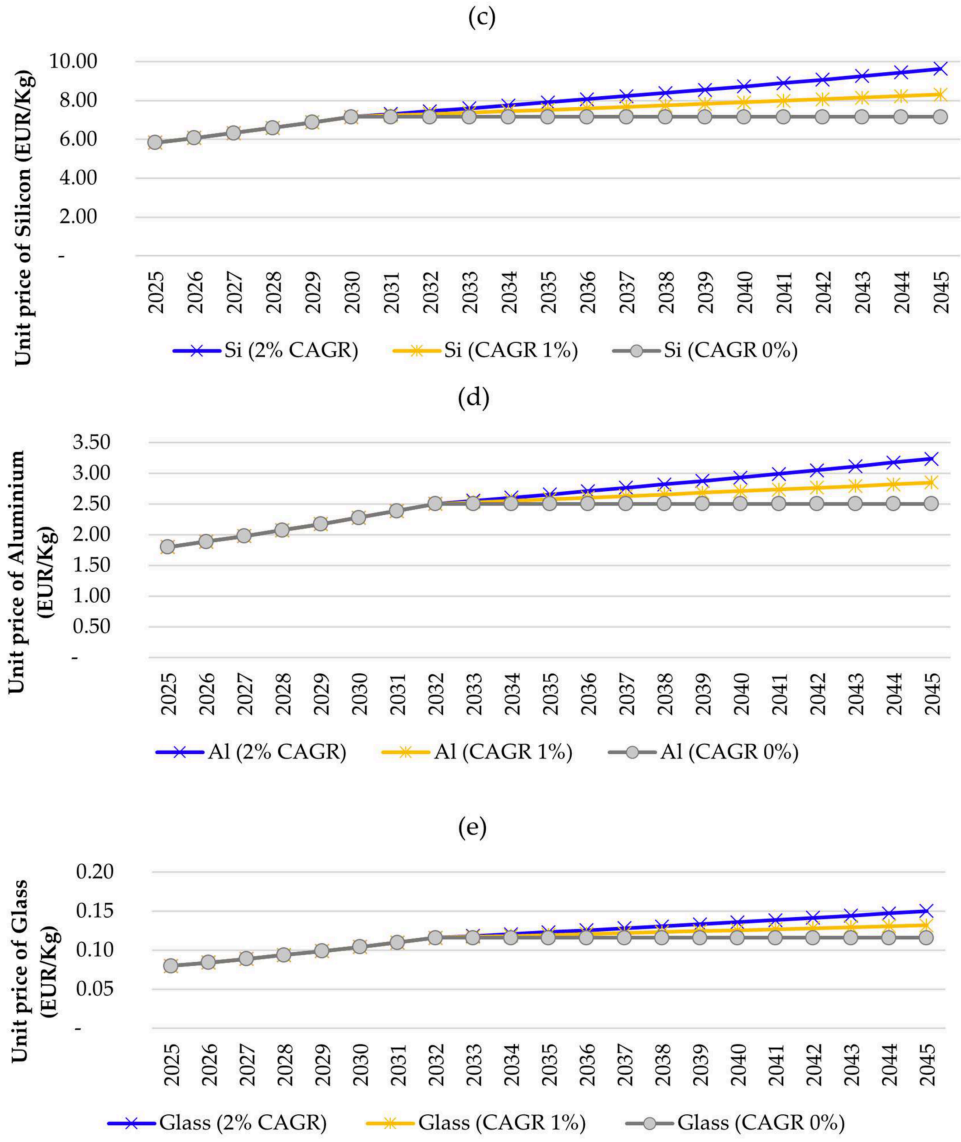


Figure 7. Annual variation of the unit prices of the major material recovered from solar PV waste: (**a**) Copper; (**b**) Silver; (**c**) Silicon; (**d**) Aluminum; (**e**) Glass.

3.4. Cost to Recycle PV Waste and Recover Al, Ag, Si, Cu and Glass

Using the methodology outlined in Appendix B, the cost to recover aluminum, silver, silicon, copper and glass in a 4000 t/yr capacity plant using the proposed recycling method is estimated to be about €659.10 per ton of waste (Table 14).

Further, using recovered material allows evasion of energy intensive processes and associated costs like the carbothermic reduction of silicon and the Siemens process. The recovered silicon would, however, need to be recast into ingots, wafers and silicon cells to enable subsequent assembly of the module, the costs for which are accounted for. Additionally, it is important to note that additional purification processes of the recovered material (other than those covered in the study) might be necessary. Due to the lack of reliable literature on the cost estimate for such processes, this study assumes a crude factor of 20% added on top of the resultant cost estimate. All negative costs in Table 15 indicate that the material quantity was in excess when manufacturing 15 kWp of PV and is therefore deducted from the overall cost. This excess quantity can be used for the next batch of manufacturing.

Table 14. Cost to recycle 1 t of waste in a 4000 t/yr plant using the proposed FRELP method.

Cost Type	Cost (€/t)
CAPEX (Facility and equipment)	189.04
Energy	26.58
Transportation	159.65
Chemicals	19.83
Labor and other operational expenses	264.00
TOTAL	**659.10**

Table 15. Cost estimate (in 2025) to manufacture solar PV using recovered recycled material.

Cost Type		Cost	Unit
Material	Glass	0.00	€/15 kW_p
	Aluminum	−182.54	€/15 kW_p
	Silicon	−26.77	€/15 kW_p
	Silver	−402.53	€/15 kW_p
	Copper	265.22	€/15 kW_p
	Lead	0.33	€/15 kW_p
	Tin	20.97	€/15 kW_p
	EVA	143.40	€/15 kW_p
	Backsheet	11.55	€/15 kW_p
Manufacturing process	Cost of recycling (From Table 14, Section 3.4)	0.66	€/15 kW_p
	Additional purity charges (assumed 25% of the value of the recovered materials from Table 14 and added on top)	293.72	€/15 kW_p
	Ingot/wafer manufacture	0.035	€/15 kW_p
	Solar cell manufacture	0.05	€/15 kW_p
	Module assembly	0.11	€/15 kW_p
Subtotal (€/15 kW_p)		**783.29**	**€/15 kW_p**
TOTAL (€/W_p)—If recovered material is available cost-free		**0.050**	**€/W_p**
TOTAL (€/W_p)—If recovered material is purchased		**0.086**	**€/W_p**

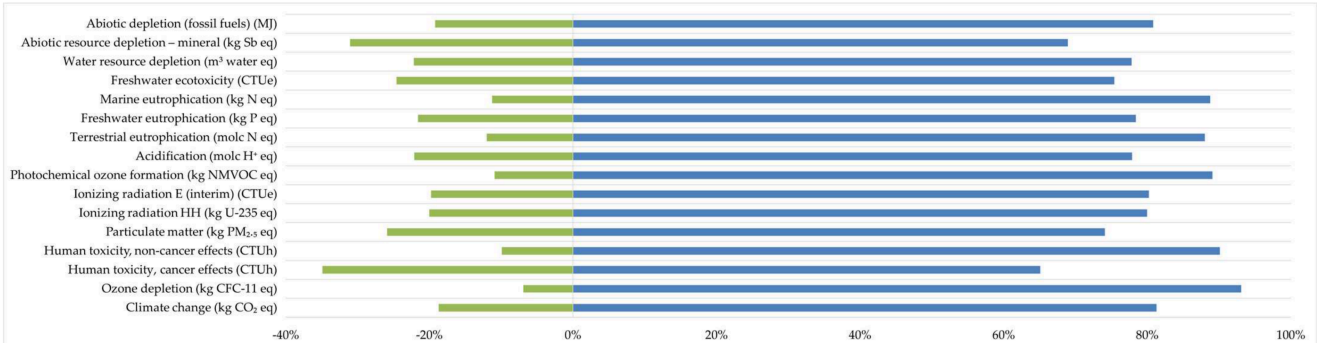
Two cost estimates are prepared—the first case in which the recycler is assumed to be the manufacturer and, therefore, need not purchase the recovered material; and the second case where the manufacturer is independent of the recycler and the former has to purchase the recovered material from the latter at the market prices estimated in Table 6 of Section 2.3.

This study reveals that the cost to manufacture PERC in Europe using recycled material is about 0.050 €/Wp when the material is available free of charge and 0.086 €/Wp when the material has to be purchased. The existing literature reports that as of 2024, it costs about 0.225 €/Wp to manufacture PERC PV panels in Europe using virgin material [60]. Hence, subject to the assumptions of this study, manufacturing solar PVs using recycled material in Europe could incur indicative savings ranging between 60 and 77% of the manufacturing costs compared to manufacturing using virgin material.

Notably, if this analysis were conducted for the Chinese context, the opposite outcome may be observed. In the Chinese context, the economic advantage of recycling-based manufacturing may be less pronounced due to the highly cost-competitive vertically integrated virgin-material PV supply chains, lower labor costs and greater economies of scale that dominate Chinese manufacturing [61]. It is reported that globalized PV supply chains generated approximately USD 36 billion in cost savings for China between 2008 and 2020, which is around five times higher than the savings observed in Germany, highlighting the strong economic advantages associated with China's existing virgin-material manufacturing ecosystem [62].

3.5. Environmental Impact Assessment

Figure 8 presents a side-by-side comparison of environmental impacts associated with manufacturing 1 ton of c-Si PV using virgin materials (VMM) versus recycled materials (RMM) recovered through the proposed FRELP-based pathway. The data for this comparison were based on the secondary life cycle inventory (LCI) and life cycle assessment (LCA) data sourced from the existing literature which also analyzes the impact of FRELP-based recycling of PV, albeit one that is different from the process analyzed in this study. The results should therefore be interpreted as an indicative screening-level comparative assessment rather than a fully process-specific quantification of the environmental impact of the proposed FRELP configuration.



	Climate change (kg CO_2 eq)	Ozone depletion (kg CFC-11 eq)	Human toxicity, cancer effects (CTUh)	Human toxicity, non-cancer effects (CTUh)	Particulate matter (kg $PM_{2.5}$ eq)	Ionizing radiation HH (kg U-235 eq)	Ionizing radiation E (interim) (CTUe)	Photochemical ozone formation (kg NMVOC eq)	Acidification (molc H^+ eq)	Terrestrial eutrophication (molc N eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)	Freshwater ecotoxicity (CTUe)	Water resource depletion (m^3 water eq)	Abiotic resource depletion – mineral (kg Sb eq)	Abiotic depletion (fossil fuels) (MJ)
VMM	9350	0	0	0	4	2310	0	31	49	90	6	9	21,500	34,100	11	144,000
RMM	-2,150	0	0	0	-2	-578	0	-4	-14	-12	-2	-1	-7,010	-9,720	-5	-34,200

Figure 8. Comparative environmental assessment of virgin-material-based manufacturing (VMM) versus recycled-material-based manufacturing (RMM) [63].

Key points to note in relation to this assessment are as follows:

- The FRELP-type processes proposed in this study differ from the FRELP pathway reported by Latunussa et al. and should therefore be interpreted as an indicative screening-level comparative assessment rather than a fully process-specific quantification of the environmental impact of the proposed FRELP configuration [63]. The former relies on light-pulse delamination, salt etching and additional energy-intensive purification steps like zone refining so that the resulting recovered materials are pure enough for remanufacture of PV panels. The pathway reported by Latunussa et al. primarily utilizes energy-intensive thermal treatment for bulk material separation without explicitly demonstrating solar-grade purity. Given that the proposed FRELP pathway replaces several energy-intensive thermal treatment stages with light-pulse delamination and molten salt etching, differences in process energy demand and associated environmental burdens are expected. However, process-specific primary inventory data are not yet available to quantitatively verify the magnitude of these differences. Nonetheless, the secondary inventory data from Latunussa et al. [63] provide a useful indicative comparative basis for evaluating the potential environmental benefits associated with high-value PV material recovery and avoided virgin material production.
- The impacts reported for virgin-material-based manufacturing (VMM) represent the absolute life cycle burdens associated with primary raw material extraction and processing and are therefore strictly positive across all impact categories. In contrast, impacts reported for recycled-material-based manufacturing (RMM) represent net impacts, where recycling process burdens are offset against avoided virgin material

production; negative values thus indicate net environmental benefits. To enable comparison across indicators with widely differing magnitudes, results are presented as percentage contributions in a stacked horizontal bar chart. Once again, given the use of secondary inventory data, the results should be interpreted as comparative indicators of environmental performance rather than precise absolute impact values.

- Findings of the comparative environmental impact assessment are as follows:
- For climate change, VMM exhibits a substantial burden (9350 kg CO_2 eq per ton of PV), reflecting the energy-intensive nature of silicon purification and metal refining. The recycling-based pathway shows a net benefit of −2150 kg CO_2 eq, indicating that avoided virgin production outweighs the emissions associated with advanced recycling operations.
- Fossil resource depletion exhibits a similar pattern, where the virgin pathway consumes 144,000 MJ of fossil energy, while recycling-based manufacturing achieves a net saving of −34,200 MJ.
- Water resource depletion shows one of the largest absolute contrasts, with virgin-based manufacturing requiring over 34,000 m^3 water eq per ton, compared to a net reduction of −9720 m^3 under the recycling-based pathway. This reflects the highly water-intensive nature of virgin silicon and metal production.
- Toxicity- and air-pollution-related indicators show substantial improvements under recycling-based manufacturing, with net reductions of approximately 50–90% relative to virgin-based production. Human toxicity and freshwater ecotoxicity impacts, which are dominated by primary metal extraction and refining, are particularly reduced due to the avoidance of silver, copper, and aluminum mining and smelting activities.

Overall, the results indicate that while virgin-based manufacturing imposes substantial environmental burdens across all assessed indicators, FRELP-based recycling enables significant net environmental benefits by displacing primary material production. The magnitude of these benefits should be interpreted with caution until process-specific primary LCI data for the proposed FRELP pathway become available.

3.6. Deployment Reality and Policy Landscape

The results of this study indicate that, under German/EU conditions, manufacturing photovoltaic (PV) modules using recycled materials could potentially be more cost-effective than using virgin materials, with indicative cost savings of 60–77%. Despite this apparent economic advantage, high-recovery recycling pathways such as FRELP are not widely deployed in Germany. It is also reported that by 2050 Germany will have to confront PV waste as much as seven times its current capacity, prompting the need for expanding its infrastructure. Additionally, Germany primarily deploys mechanical recycling methods that mostly recover glass and aluminum alone, whereas the recovered solar cell components remain of substandard purity for reuse applications [64].

While the low technology readiness level (TRL) of advanced FRELP measures is a factor for this insufficient capacity, the key issue lies in the German/EU policy landscape. Germany currently classifies PV waste as 'electronic waste' under the EU Waste Electrical and Electronic Equipment (WEEE) Directive, transposed into national law via the ElektroG (Electrical and Electronic Equipment Act). PV modules have been included since 2012, mandating producer responsibility for collection and recycling [65]. Key policy mandates and policy instruments enforced are summarized in Table 16.

Table 17 presents the gaps identified in the current framework along with recommendations to improve the status quo.

Table 16. List of key policy standards and instruments currently enforced in Germany.

Policy Instrument	Description	Impact on PV Recycling	Source
Minimum recovery and recycling targets (85%/80%)	Sets mass-based recovery and recycling thresholds, determined by the weight of the recovered material and not by material type.	Focuses on quantity, not quality of recycling. Low composition, yet high value components like silver are lost.	[66]
B2C financing allocation under Extended Producer Responsibility (EPR)	Applies to household rooftop solar. Producers (manufacturers/importers) must pay for collection and recycling. Consumers can return panels free of charge.	Homeowners do not bear the cost, which makes it easy and convenient to recycle panels properly; but does not incentivize high-value recovery.	[65]
B2B financing allocation	Applies to commercial or industrial systems (e.g., solar farms, factories). The responsibility is negotiated contractually between the buyer and seller. Often, the system owner pays for recycling.	Recycling is not always free, and costs depend on agreements made during purchase. Offers weaker incentive than B2C for recycling. Quality of recycling is also not addressed.	[65]
End-of-Waste Criteria (Waste Framework Directive)	A regulatory standard that defines when recovered materials can re-enter the market. Promotes secondary/recycled material markets.	Supports circularity; effectiveness limited by insufficient high-quality material recovery.	[67]
Stiftung Elektro-Altgeräte Register (EAR) Registration System	All producers are required to register before market entry and submit regular reports on quantities placed on the market and collected at end-of-life.	The Stiftung EAR database enables full traceability of PV modules across their lifecycle, ensuring waste streams can be accounted for and penalizes producers for evasion of responsibility. However, its focus is primarily on compliance and quantity-based targets, rather than incentivizing high-quality or high-value material recovery.	[68]

Table 17. Policy gaps and recommended interventions for PV recycling in Germany.

Policy Gap	Implications	Recommended Policy Measures	Source
Lack of financial incentives like subsidies, grants or financial risk-sharing mechanisms for technological innovation and infrastructure expansion	Limits scaling of high-recovery processes (e.g., FRELP); deters private investment	Introduce CAPEX subsidies, tax credits, low-interest loans, and public–private partnerships (PPPs) to support infrastructure scaling	[69]
Targets based on mass recovery (85%) rather than material value or purity	Encourages recovery of bulk materials (glass, aluminum) while losing high-value materials (e.g., silver, silicon)	Implement value-based or material-specific recovery targets; introduce critical material recovery quotas	[11]
Absence of standards that encourage PV panels to be designed for recyclability	Increases technical difficulty and cost of material recovery at end-of-life	Introduce eco-design regulations, including modular design, reduced material complexity, and recyclability criteria	[70]
Misalignment between EPR fees and actual recycling costs	Discourages investment in advanced recycling; promotes lowest-cost compliance options	Reform EPR to include eco-modulated fees. Instead of every producer paying roughly the same recycling fee, the fee is lowered depending on how easy the panel is to dismantle and recycle. This would also encourage producers to manufacture easy-to-recycle PV panels to reduce the EPR fees to be paid	[64]

4. Conclusions

This study set out to evaluate whether advanced recycling of end-of-life crystalline silicon photovoltaic (c-Si PV) modules is environmentally and economically justified in Europe, using Germany as a representative early-deployment case. Projected end-of-life PV waste volumes indicate that Germany alone is expected to generate between 3.3 and 5.6 million tons of PV waste by 2045, and existing low-value mechanical recycling routes are insufficient to manage this stream sustainably.

This study demonstrates that using advanced FRELP-based recycling techniques is economically and environmentally justified to help manage this wave of PV waste. It identifies potential to transform this waste into a strategic secondary resource base, particularly silicon, silver, aluminum, copper, and low-iron glass, thereby enabling substitution of virgin materials. The recovery of these materials alone yields approximately €1174.88 per ton of panels recycled, indicating significant economic incentive for recycling the panels using high-recovery methods.

Further economical assessment indicates that manufacturing PV modules using recycled materials can reduce production costs by approximately 60–77% compared to virgin-material-based manufacturing in Europe. These savings arise primarily from avoiding energy-intensive upstream processes such as mining, silicon purification via the Siemens process, and primary metal refining.

From an environmental perspective, the recycling-based pathway delivers net benefits across all assessed impact categories, including climate change, fossil resource depletion, water use, and toxicity. The avoided impacts from primary material extraction and processing outweigh the additional burdens associated with advanced recycling and purification, resulting in substantial reductions in greenhouse gas emissions and resource consumption per ton of PV manufactured.

Overall, the findings confirm that PV recycling in Europe is not merely desirable but essential for environmental integrity, cost reduction, and long-term industrial resilience. The current policy framework is effective in ensuring collection and regulatory compliance, but remains structurally inadequate for enabling high-value, economically viable recycling systems. The absence of targeted financial incentives, value-based recovery metrics, and aligned economic signals explains the limited deployment of advanced recycling pathways despite their demonstrated techno-economic and environmental benefits. Therefore, targeted policy support and investment in advanced recycling infrastructure will be key to realizing these benefits at scale.

All considered, there remain several areas that have not been fully explored within the scope of this study, which present opportunities for investigation in future research.

- Overlooking low-value material: This study focuses only on the recovery of major materials such as glass, silver, copper, aluminum, and silicon, while excluding components like the backsheet, encapsulant, junction box, and solder materials (tin and lead). As a result, this may lead to a slight underestimation of total recovery potential, associated costs, and environmental impacts, and future studies should aim to incorporate these additional material streams for a more comprehensive assessment.
- Regional specificity: The findings are based on German and the broader European conditions, particularly reflecting energy prices, labor costs and regulatory frameworks, and may not be directly transferable to other regions. Expanding the analysis to other regions would improve the generalizability of the results.
- Technological evolution: This study limits its focus only to Al-BSF and PERC c-Si panels. However rapid advancements in PV module design (e.g., reduced silver content, new cell architectures) may influence future material recovery potential and

economic value, which is not captured in this study. Incorporating next-generation PV technologies represents an important direction for further research.

- Exclusion of broader system dynamics: Market fluctuations, policy incentives, and supply chain disruptions are not explicitly accounted for, although they may significantly affect real-world feasibility. Future work should integrate these factors to provide a more holistic evaluation of photovoltaic recycling systems.
- Limited available data on the recycling processes such as salt etching, light-pulse delamination and zone refining may lead to discrepancies in results; therefore, further investigation is required in future studies.

Future work may incorporate probabilistic uncertainty approaches such as Monte Carlo simulation to further evaluate the sensitivity of economic outcomes to variations in material prices, recovery efficiencies, energy costs, and plant-scale operating assumptions.

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Abbreviations

The following abbreviations are used in this manuscript:

Al-BSF	Aluminum Back Surface Field
B2B	Business to Business
B2C	Business to Customer
CAPEX	Capital Expenditure
CAGR	Compound Annual Growth Rate
CRF	Capacity Recovery Factor
c-Si	Crystalline Silicon
ElektroG	Elektronikergerätegezetz (Electrical and Electronic Equipment Act)
EoL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
EUR	Euro (Currency)
EVA	Ethylene Vinyl Acetate
FRELP	Full Recovery of End-of-Life Panels
IEA	International Energy Agency
Ionizing HH	Ionizing Herbig-Haro
IRENA	International Renewable Energy Agency
LCI	Life Cycle Inventory
LCA	Life Cycle Assessment
MG-Si	Metallurgical Grade Silicon
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PERC	Passivated Emitter Rear Contact
PPP	Public-Private Partnership

PV	Photovoltaics
PVPS	Photovoltaic Power Systems Program
RMM	Recycled Material based Manufacturing
SG-Si	Solar Grade Silicon
Stiftung EAR	Stiftung Elektro-Altgeräte Register
TOPCon	Tunnel Oxide Passivating Contact
TRL	Technology Readiness Level
VMM	Virgin Material based Manufacturing
WEEE	Waste Electrical and Electronic Equipment

Appendix A

Appendix A.1. Input Data

(a) Cumulative installed capacity between 2002 and 2025 and projected installations between 2026 and 2045 were obtained from Fraunhofer [71].

(b) Power to weight ratio was obtained between 2002 and 2025 for every 5-year interval from various online sales platforms for new and secondhand PV panels (Table A1). The ratios for upcoming models from 2030 till 2045 were assumed based on IRENA [5]. Worth noting that

- All figures are based on standard 60-, 72-, or 144-cell commercial panels (not lightweight, flexible, or bifacial niche products).
- When manufacturers' list weight was ranged, the midpoint or most common configuration was selected.

Table A1. Power to weight ratio of solar PV derived to convert installed capacity in W to installed weight in kg.

Year	Manufacturer	Model	Power (W)	Weight (kg)	Power-Weight Ratio (W/kg)	Source
2000	SF 200/2	SF 200/2	200	24.7	8.10	[72]
2005	Tenesol	TE2000 200 Wp	200	22.6	8.85	[73]
2010	Tenesol	TE2000 210 Wp 20P1-A1	210	19	11.10	[74]
2015	Energetica	E-2000 270	270	22.3	12.10	[75]
2020	JA Solar	JAM60S10-340/MR	340	19	17.90	[76]
2025	JinkoSolar	Tiger Neo N-type 440 W	440	22	20.00	[77]
2030	-	-	-	-	22.00	[5]
2035	-	-	-	-	24.00	
2040	-	-	-	-	30.00	
2045	-	-	-	-	30.00	

(c) Using the cumulative installed capacity and the power-to-weight ratio, the cumulative installed mass of the PV panels was estimated.

$$\text{Cumulative installed mass M(t) in kg} = \frac{\text{Cumulative installed capacity in W}}{\text{Power to weight ratio in W per kg}}$$

Appendix A.2. Selection of Weibull Parameters

Table A2. Weibull parameters used in this study for estimation of waste quantities.

Parameter	Optimistic	Baseline	Pessimistic	Citation
T (av. lifetime)	30 years	25 years	20 years	[34]
α (shape factor)	5.3759	5.3759	5.3759	[35]

Appendix A.3. Building the Waste Model

(a) Set up matrix between installed year (y) and target year (t) to estimate age of the panel post its installation in a given year (refer to Table A3).

(b) For each (t,y), estimate cumulative failure Ft,y:

$$F(t) = 1 - e^{\left(-\left(\frac{t-y}{T}\right)^{\alpha}\right)}$$

where

y is the year in which the solar panels are installed;

t is the target year when failure of the solar panel is to be estimated post installation.

In year y

T is the average lifetime or scale factor;

α is the shape factor;

F(t) is the cumulative probability that a panel installed in year y fails by year t.

(c) The Weibull parameters specified in Appendix A.2 were applied to obtain F(t) each year under the optimistic, baseline and pessimistic scenarios.

(d) Apply the following equation to obtain the "Total" column in Table A3.

$$\text{Cumulative waste in year } t = \sum_{y=2002}^{t} F(t,y) \times M(t)$$

M(t) is the aggregated mass of solar panels installed in year t.

F(t,y) is the failure rate of panels installed in year y in year t.

Table A3. Matrix for estimating the waste throughput.

Year Installed (y) →	**2002**	**2003**	**- - - -**	**2045**	**Total**
Years After Installation (t) ↓			**Weight (Tonnes)**		
2002	0.00	0.00	**- - - -**	0.00	0.00
2003	4.24×10^{-4}	0.00	**- - - -**	0.00	0.00
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
2045	2.09×10^{4}	1.72×10^{4}	**- - -**	0.00	3.66×10^{6}

Appendix B

Appendix B.1. CAPEX for a Medium-Sized Plant with 4000 Ton per Year Capacity

Appendix B.1.1. The Facility

The cost of the construction of the facility, including architectural, civil and electromechanical works, excluding recycling equipment cost (Table A4) was estimated by assuming the size of the 4000 t/year plant and multiplying it by the latest available unit cost rate in €/m^2.

Table A4. Estimate of the construction cost of the facility.

Description	**Value**	**Rationale**	**Citation**
Assumed size of the plant	6000 m^2	Selected based on the average size of waste-energy plant in Germany, which is given to range between 5000 and 8000 m^2	[78]
Unit construction cost assumed	1250 €/m^2	The selected cost represents the cost of a high-end warehouse in Dublin, Ireland. The value range given in the literature was between 1050 and 1250 €/m^2	[79]
Cost of construction	**€7500,000**		

CAPEX for 4000 t/year recycling plant facility = €7,500,000

Appendix B.1.2. Salt Etching Equipment

Breakdown of the cost of equipment needed for the salt etching system is indicated in Table A5. It is worth noting that this cost is for a plant capacity of 1 ton per day capacity.

Table A5. Breakdown of costs for the salt etching system [80].

Equipment	Cost (Euro)
Molten salt reactor	4294.27
Glass fiber components	73.25
PV container	1225.27
Electric heater	700
Equipment assembly labor cost	48,275.74
Total	**54,568.53**

This cost was subsequently scaled up to estimate the cost for the salt etching equipment needed for a plant with capacity 4000 t/yr (~15 t/day), as assumed in this study. The scaling is done using the learning curve theory which is expressed by the following equation from [81]:

$$C_x = C_o \times \left(\frac{Q_x}{Q_o}\right)^{\beta}$$

where

C_x is the cost to produce the xth unit and x representing the cumulative production up to and including the xth unit of production;

C_o is the reference cost or initial cost;

Q_x capacity to produce x units;

Q_o is the reference or initial capacity;

β is the learning or experience parameter.

Applying Q_o from [80] and costs from Table A5 to this this equation to estimate the cost of a 15 t/day plant:

$$\text{Initial capacity given in the literature}, Q_o = 1\text{t/day}$$

$$\text{Cost for 1 t/day plant}, C_o = €54,568.53$$

$$\text{Capacity to be scaled to}, Q_x = 15\ \text{t/day}$$

$$\text{Learning parameter}, \beta = 0.75\ (\text{assuming modest economies of scale})$$

$$\text{CAPEX for 15 t/day plant}, C_t = C_o \times \left(\frac{Q_x}{Q_o}\right)^{\beta} = 54,568 \times \left(\frac{15}{1}\right)^{0.75}$$

CAPEX for 15t/day salt etching equipment = €415,916.82

Appendix B.1.3. Light-Pulse Delamination Equipment

Light-pulse delamination technology is still in prototype phase at the time of this study, and therefore, a comprehensive price estimate was not available, Therefore, the cost of pyrolysis delamination equipment of comparable capacity was identified from the existing literature and used as an estimate for the cost of the light-pulse delamination system, although in reality, the light-pulse system should cost less due to its simpler system

components. Assumptions were adopted to prepare a cost build up for a 4000 t/year plant. The CAPEX value of the pyrolysis equipment is deduced based on [24].

CAPEX for a 3000 t/year pyrolysis-based plant = $5,444,410 = € 4,683,738.71

It is assumed that the pyrolysis equipment constitutes 30% of the above CAPEX.

$$\begin{aligned}\text{Therefore, cost of pyrolysis equipment} &= 30\% \times €4,683,738.71\\ &= €1,405,121.61\end{aligned}$$

Thus, cost of light-pulse delamination equipment = €1,405,121.61

Appendix B.1.4. Zone Refining Equipment

Due to a lack of reliable data at the time of this study on the cost of zone refining equipment, the comparable cost of a high-end production crystal growth furnace was utilized. It is reported that such a high-end furnace for crystal sizes 6–12 inches would cost between $300,000 and $1,500,000 [82]. Accordingly, the associated cost for a medium sized 4000 t/year plant was assumed to be within this range as shown below.

CAPEX for zone refining equipment = €345,000.00

Appendix B.1.5. Total CAPEX and Estimate of Annualized CAPEX per Ton of PV Waste

Adding up the estimates from Appendices B.1.1–B.1.4 yields €9,666,038.43 (Table A6).

Table A6. Sum of all CAPEX involved.

CAPEX Type	Cost (€)
Facility construction	7,500,000
Salt etching equipment	415,916.82
Light-pulse delaminator	1,405,121.61
Zone refining equipment	345,000.00
Total	**€9,666,038.43**

Subsequently, the Capital Recovery Factor (CRF) is estimated using the equation from [83]:

$$\text{CRF} = \frac{\text{r} \times (1+\text{r})^{\text{n}}}{(1+\text{r})^{\text{n}} - 1}$$

where

r is the discount rate;

n is the economic life of the project.

The below assumptions are made to estimate the annualized CAPEX per ton of waste.

Economic life of the plant, n = 25 years (assumed).

Discount rate, r = 6% (based on [84]).

$$\begin{aligned}\text{Therefore, CRF} &= \frac{\left(6\% \times (1+6\%)^{25}\right)}{(1+6\%)^{25}-1}\\ &= 0.0782\end{aligned}$$

$$\begin{aligned}\text{Annualized CAPEX per tonne of waste} &= \frac{\text{Total CAPEX} \times \text{CRF}}{\text{Plant capacity}}\\ &= \frac{9,666,038.43 \times 0.0782}{4000}\end{aligned}$$

$$\textbf{Annualized CAPEX per tonne of waste} = \mathbf{189.04}\ \frac{€}{year.tonne}$$

Appendix B.2. Energy Costs for the Recovery of the Material

Only electricity costs are involved for the recovery of material from EoL panels, as follows.

Appendix B.2.1. Electricity Consumed by Light-Pulse Delamination Equipment

Using energy consumed by the equipment from [30] and mass-to-area ratio of a solar panel from [21], the total energy consumed for light pulse delamination was estimated as follows:

$$\text{Energy consumed} = 0.65 \text{ kWh/panel}$$

$$\text{Average area of a solar panel} = 1.6 \text{ m}^2 \text{ (Assumed)}$$

$$\text{Mass-to-area ratio of a solar panel, as of 2021} = 11.6 \text{ kg/m}^2$$

$$\begin{aligned}\text{Average mass per module} &= \frac{\text{Mass to area ratio}}{\text{Average area of a panel}} \\ &= \frac{11.6}{1.6} \\ &= 18.56 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{Number of PV modules per tonne of waste} &= \frac{1000}{18.56} \\ &= 54 \text{ modules per tonne}\end{aligned}$$

$$\begin{aligned}\text{Energy needed to delaminate 1 t of waste} &= \text{No. of modules} \times \text{Energy consumed/panel} \\ &= 54 \times 0.65\end{aligned}$$

$$\text{Energy consumed to delaminate 1 t of waste} = 31.5 \frac{\text{kWh}}{\text{tonne of waste}}$$

Appendix B.2.2. Electricity Consumed by Salt Etching Process

The salt etching process is only applied to the Si solar cells, after the frame, glass, junction box and the EVA encapsulant are removed.

One ton of solar PV waste contains approximately 47 kg of solar cells (based on [31]). Energy consumed for the salt etching process, electrodeposition copper and its recovery were deduced from [4], [85] and [1] respectively.

$$\text{Energy consumed for salt etching of 1 kg of solar cells} = 0.813 \text{ kWh/kg}$$

$$\begin{aligned}\text{Energy consumed to treat all the Si cells in 1t of waste} &= 47 \times 0.813 \\ &= \frac{38.21 \text{ kWh}}{\text{tonne of waste}}\end{aligned}$$

Appendix B.2.3. Electricity Consumed for Electrodeposition of Copper

$$\text{Energy consumed for deposition of 1 kg of copper} = 2.5 \text{ kWh/kg.Cu}$$

$$\text{Copper recovered per ton of PV waste} = 4.38 \text{ kg}$$

$$\begin{aligned}\text{Energy consumed to recover copper from 1t of PV waste} &= 2.5 \times 4.38 \\ &= \frac{10.95 \text{ kWh}}{\text{tonne of waste}}\end{aligned}$$

Appendix B.2.4. Electricity Consumed Zone Refining of Si to Remove Dopant Impurities

Due to the limited literature on energy consumed for zone refining of silicon, the energy consumed for the purification of Si using electrochemical refining was utilized for this study taken from Mulazzani et al. [31].

$$\text{Energy consumed for zone refining of Si} = \frac{63.4 \text{ kWh}}{\text{tonne of PV waste}}$$

Appendix B.2.5. Total Electricity Consumption

Sum of all the electricity consumption estimates and associated costs from Appendices B.2.1–B.2.4 are provided in Table A7. Unit cost of electricity is considered for industrial enterprises in Germany as of January 2025, which is around 0.18 €/kWh [86].

Table A7. Sum of all electricity consumption-related expenses.

Description of Step	Electricity Consumed (kWh/Ton of PV Waste)	Electricity Unit Rate (€/kWh)	Cost (€)
Light-pulse delamination	31.5	0.18	5.67
Salt etching	38.21	0.18	6.88
Electrodeposition of copper	10.95	0.18	1.97
Zone refining of silicon	63.4	0.18	11.41
Total	**147.65**		**25.93**

Appendix B.3. Transportation of PV Waste

Appendix B.3.1. Fuel Consumption

Distance covered for the transportation of PV waste is broken down as indicated in Table A8. Key input parameters are as follows, assuming a 12–24 t truck is carrying out the freight operations:

- Diesel consumption: 0.063 Liters/tonne.km [87].
- Diesel price as of 1 October 2025: 1.6 €/Liters [88].
- Only a one-way trip is considered.

Table A8. Estimate of fuel expenses for transport of waste.

Route	Recommended Distance Range from Literature (km)	Distance (km) Used in This Study for 1 Ton of Waste	Diesel Consumption of a 12–24 t Truck (Liters/Tonne.km)	Diesel Price (€/L)	Cost (€/Ton.Trip)	Sources and Notes for the Assumption on Distances Assumed
Collection of PV waste from consumers	2.0–3.2 km	3.2	0.063	1.6	0.32	Distance is based on study by Schmidt whereby closing recycling centers in Bavaria increased the median travel distance from 2.0 to 3.2 km [89].
Collection point to PV recycling site	~400 km	400	0.063	1.6	40.32	Widely used PV-recycling LCAs use ~400 km as the base distance from collection point to centralized recycling plant [11].
Transport of glass to specialist recycling facility	100–333 km	333	0.063	1.6	33.57	Existing LCA estimated: collection to treatment plant is approx. 100 km; treatment to flat glass manufacturer is between 167–333 km [90].
Transport of Al to specialist recycling facility	200–250 km	250	0.063	1.6	25.2	International Aluminum/IRT report notes EoL scrap usually collected locally/nationally, closer than 100 km but up to 200–250 km for EoL streams [91].
Transport of ash, sludge and other recycling waste to landfill	30–120 km	120	0.063	1.6	12.1	Recent LCA literatures use 30–120 km as typical distances for landfilling of residues [92].
Total		**1106.2**			**111.50**	

Appendix B.3.2. Vehicle, Driver, Tolls and Other Miscellaneous Expenses

This study provides an estimate for expenses related to the driver, vehicle ownership, vehicle operations and maintenance and tolls. Assuming the case of a 12–24 t truck with one-way travel distance of 1106.2 km, the estimates are as follows.

Driver Expenses:

As of 2025, it is reported that the average wage of a truck driver is 23.33 €/h [93]. Assuming the truck travels at an average speed of 90 km/h, the average time spent by the driver is estimated to be around 12 h per trip.

$$\text{Therefore, driver costs} = \frac{€23.33}{\text{hr}} \times 12 \text{ hours} = €280 \text{ per trip}$$

Vehicle Financing and Possession

This study assumed the following in relation to the truck used for transporting the PV waste:

- Distance travelled per year (one trip per week assumed): ~80,000 km/year;
- Truck purchase price: €80,000;
- Truck salvage price: €10,000;
- Truck lifetime, n = 15 years;
- Discount factor, r: 6%.

Capital recovery factor (CRF) estimated using the formula in Appendix B.1.5 is sourced from [83] as follows:

$$\begin{aligned} \text{CRF} &= \frac{r \times (1+r)^n}{(1+r)^n - 1} \\ &= \frac{6\% \times (1+6\%)^{15}}{(1+6\%)^{15} - 1} \\ &= 0.103 \end{aligned}$$

$$\begin{aligned} \text{Annualized vehicle CAPEX} &= (\text{Purchase price} - \text{Salvage price}) \times \text{CRF} \\ &= (€80,000 - €10,000) \times 0.103 \\ &= 7210\, €/year \end{aligned}$$

$$\begin{aligned} \text{Hence, vehicle expense per trip} &= \frac{\text{Annualized CAPEX}}{\text{Yearly mileage}} \times \text{Distance covered per trip} \\ &= \frac{7.210}{80,000} \times 1106.2 \end{aligned}$$

$$\text{Vehicle financing expense per trip} = €99.69 \text{ per trip}$$

Vehicle Operations and Maintenance (O&M)

Annual maintenance expenses for a 40 t truck in Germany as reported in the existing literature is about €3459 per annum for an annual mileage of 127,600 [94].

Based on this, the annual maintenance cost of a 12–24 t truck is expected to be 70% of the annual expenses of the 40 t truck [94]. Subsequently, the maintenance cost of the truck per trip is estimated as follows:

$$\begin{aligned} &\text{Vehicle O\&M expenses} \\ &= \frac{\text{Expense of 40 Ttruck} \times 70\%}{\text{Distance travelled per trip in source literature}} \\ &\times \text{Distance travelled per trip in this study} \\ &= \frac{3450 \times 70\%}{127,600} \times 1106.2 \end{aligned}$$

$$\text{Vehicle O\&M expenses} = €20.94 \text{ per trip}$$

Toll Fees

The toll gate fee for a 12 to18 t truck with class 1 carbon emission classification is €0.35 per km according to Toll Collect GmbH since July 2024 [95].

$$\begin{aligned}\text{Toll expenses per trip} &= \text{Toll rate} \times \text{Distance covered per trip}\\ &= €0.35 \times 1106.2\end{aligned}$$

$$\text{Toll expenses per trip} = €387.17 \text{ per trip}$$

Total Vehicle, Driver, Tolls and Other Miscellaneous Expenses

The sum of all the expenses estimated in Appendix Driver Expenses to Appendix Toll Fees is provided in Table A9.

Table A9. Summary of costs of the driver, vehicle ownership and other miscellaneous expenses.

Description of Expense	Expense	Unit
Driver	280.00	€/trip
Vehicle financing and possession	99.69	€/trip
Vehicle O&M	20.94	€/trip
Toll fees	387.17	€/trip
Subtotal 1	**787.80**	€/trip
Additional administrative/indirect costs (Assumed 10% on top)	78.78	€/trip
Subtotal 2	866.58	€/trip
Total (Assuming 18 t of payload per trip)	**48.14**	€/ton.trip

Total Transportation Expenses

A summary of all transportation expenses estimated in Appendices B.3.1 and B.3.2 are provided in Table A10.

Table A10. Total costs associated with transportation.

Expense Type	Cost (€/Ton.Trip)
Fuel	111.50
Driver, vehicle financing/possession, O&M, tolls, admin costs	48.14
Total	**159.65 €/ton**

Appendix B.4. Chemicals (For the Salt Etching Process)

Table A11 provides the cost of the chemicals needed for the salt etching process considering wholesale unit prices of the chemicals. Quantity of chemicals needed per ton of waste is based on estimates by Gao et al. [4].

Table A11. Cost of chemicals needed for the salt etching process.

Chemical Name	Quantity (kg/Ton of PV Waste)	Unit Price (€/kg) as of 2 October 2025	Cost of Chemicals Required Per Ton of Solar PV Waste (€/Ton of Waste)	Source for the Wholesale Unit Rates
NaOH	23.124	0.255	5.89	[96]
KOH	27.26	0.39	10.63	[97]
Sub-total			**16.53**	
Total (with 20% contingency add-on)			**19.83**	

Appendix B.5. Labor Expenses

Labor estimates were prepared based on the following assumptions in Table A12:

Table A12. Assumptions for estimation of labor costs.

Assumption Type	Value	Source/Assumption
Plant capacity	4000 t/year	Assumed for this study.
Operating days	266 days	Excluding weekends and public holidays.
Daily processing capacity	15 t/day	Annual capacity divided by number of operating days.
Operation type	Two 8 h shifts per day	Assumption, given daily target of 15 t/day is fairly large.
Automation level	Medium	Disassembly, light-pulse delamination and zone refining are considered fully automated. Salt etching process is considered 50% automated. Sorting of the separated components is considered completely manual.
Staff wages	Assumed based on average salaries in Germany for various tiers of industrial employees in 2025	[98]

Accordingly, the cost build-up for staff wages (as of 2025) and other operational expenses is provided in Table A13.

Table A13. Assumptions for estimation of labor costs and other OPEX.

Position	Count	FTE	Annual Salary (€)	Total Salary (€/yr)	Notes
Plant Manager (day)	1.0	1.0	90,000	90,000	Single site leadership (day shift)
Operations Supervisor—Shift 1	1.0	1.0	55,000	55,000	Shift 1 safety coordination and supervision
Operations Supervisor—Shift 2 (15% higher pay than day shift)	1.0	1.0	63,250	63,250	Shift 2 safety coordination and supervision
Process Technicians—Shift 1 (4 × EUR 42,000)	4.0	4.0	42,000	168,000	Core processing staff for 06:00–14:00
Process Technicians—Shift 2 (4 × EUR 42,000 + 15%)	4.0	4.0	48,300	193,200	Core processing staff for 14:00–22:00
Quality Control Technician (day)	1.0	1.0	48,000	48,000	Day-shift based; samples QC from both shifts
Maintenance Technician—Shift 1	1.0	1.0	46,000	46,000	Shift 1 routine and ad-hoc maintenance
Maintenance Technician—Shift 2 (15% higher pay than day shift)	1.0	1.0	52,900	52,900	Shift 2 routine and ad-hoc maintenance
Logistics Coordinator (day)	1.0	1.0	38,000	38,000	Day shift; coordinates with both shifts
Safety/Environmental Officer (0.5 FTE, day)	1.0	0.5	52,000	26,000	Shared role; office-based
Administrative Support (day)	1.0	1.0	32,000	32,000	Day shift administration
Subtotal Direct Salaries	**-**	**17.5**	**-**	**812,350**	**Includes only staff wages**
Add-on for PPE expenses, insurances, maintenance and other OPEX	1.0	-	-	243,705	Assumed to be 30% on top of staff wages
Total				**1056,055**	**Per 4000 t of waste**
				264.00	**Per ton of waste**

Appendix B.6. Total Cost for Material Recovery

Table A14 provides the summary of the costs estimated from Appendices B.1–B.5, which when added is representative of the total cost to recover silicon, aluminum, copper, silver and glass from 1 ton of solar PV waste, within the assumptions of this study.

Table A14. Total cost for material recovery.

Cost Type	Cost (€/t)
CAPEX	189.04
Energy	26.58
Transportation	159.65
Chemicals	19.83
Labor	264.00
Total	**659.10**

References

1. Markert, E.; Celik, I.; Apul, D. Private and Externality Costs and Benefits of Recycling Crystalline Silicon (c-Si) Photovoltaic Panels. *Energies* **2020**, *13*, 3650. [CrossRef]
2. International Energy Agency. Photovoltaics Power Systems Program (IEA PVPS). Status of PV Module Take-Back and Recycling in Germany. IEA Photovoltaic Power Systems Programme. 2024. Available online: https://iea-pvps.org/wp-content/uploads/2024/03/IEA-PVPS-T12-27-Report-PV-Recycling-in-Germany.pdf (accessed on 15 August 2025).
3. International Energy Agency. Photovoltaics Power Systems Program (IEA-PVPS). Trends in Photovoltaic Applications 2025. 2025. Available online: https://iea-pvps.org/trends_reports/trends-2025/ (accessed on 21 November 2025).
4. Gao, S.; Chen, X.; Qu, J.; Guo, Y.; Shi, H.; Pang, F.; Guo, L.; Qu, X.; Wang, D.; Yin, H. Recycling of silicon solar panels through a salt-etching approach. *Nat. Sustain.* **2024**, *7*, 920–930. [CrossRef]
5. International Renewable Energy Agency (IRENA). End-of-Life Management: Solar Photovoltaic Panels. 2016. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf (accessed on 2 September 2025).
6. Rout, S.; Jana, P.; Borra, C.R.; Önal, M.A.R. Unlocking silver from end-of-life photovoltaic panels: A concise review. *Renew. Sustain. Energy Rev.* **2025**, *210*, 115205. [CrossRef]
7. Ansanelli, G.; Fiorentino, G.; Tammaro, M.; Zucaro, A. A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels. *Appl. Energy* **2021**, *290*, 116727. [CrossRef]
8. Badran, G.; Lazarov, V.K. From Waste to Resource: Exploring the Current Challenges and Future Directions of Photovoltaic Solar Cell Recycling. *Solar* **2025**, *5*, 4. [CrossRef]
9. Brussa, G. Photovoltaic Panels. In *Waste Flows Generated by the Energy Transition*; Springer Nature: Berlin/Heidelberg, Germany, 2025. [CrossRef]
10. Saoji, B.P.; Wankhade, S.D.; Deshmukh, J.K.; Ukarande, A.H.; Sawarkar, M.M.; Nikam, S.V.; Chavan, P.R. A Review on Recycling of Solar Photovoltaic Modules for Recovery of Metals. *Environ. Claims J.* **2024**, *36*, 63–93. [CrossRef]
11. Latunussa, C.E.; Ardente, F.; Blengini, G.A.; Mancini, L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Sol. Energy Mater. Sol. Cells* **2016**, *156*, 101–111. [CrossRef]
12. Lodovico, R. Full Recovery of End of Life Photovoltaics (New Technology to Divide the Components of Silicon Photovoltaic Panels at the End of Life), Amsterdam. 2014. Available online: https://sasil-life.com/wp-content/uploads/2018/05/Sasil-Srl-Slides-Amsterdam-23sett2014.pdf (accessed on 22 November 2025).
13. Duflou, J.R.; Peeters, J.R.; Altamirano, D.; Bracquene, E.; Dewulf, W. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. *CIRP Ann.* **2018**, *67*, 29–32. [CrossRef]
14. Azeumo, M.F.; Germana, C.; Ippolito, N.M.; Franco, M.; Luigi, P.; Settimio, S. Photovoltaic module recycling, a physical and a chemical recovery process. *Sol. Energy Mater. Sol. Cells* **2019**, *193*, 314–319. [CrossRef]
15. Li, X.; Liu, H.; You, J.; Diao, H.; Zhao, L.; Wang, W. Back EVA recycling from c-Si photovoltaic module without damaging solar cell via laser irradiation followed by mechanical peeling. *Waste Manag.* **2022**, *137*, 312–318. [CrossRef] [PubMed]
16. Huang, W.-H.; Shin, W.J.; Wang, L.; Sun, W.-C.; Tao, M. Strategy and technology to recycle wafer-silicon solar modules. *Sol. Energy* **2017**, *144*, 22–31. [CrossRef]
17. Conradi, K. *Recycling Photovoltaic Modules*; FIZ Karlsruhe: Eggenstein-Leopoldshafen, Germany, 2010. Available online: https://api.deutsche-digitale-bibliothek.de/binary/52c947ba-d36b-4234-a3c2-38a54c83c0e2.pdf (accessed on 22 November 2025).
18. Kang, S.; Yoo, S.; Lee, J.; Boo, B.; Ryu, H. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. *Renew. Energy* **2012**, *47*, 152–159. [CrossRef]

19. Dias, P.R.; Benevit, M.G.; Veit, H.M. Photovoltaic solar panels of crystalline silicon: Characterization and separation. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2016**, *34*, 235–245. [CrossRef] [PubMed]
20. Kim, Y.; Lee, J. Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent. *Sol. Energy Mater. Sol. Cells* **2012**, *98*, 317–322. [CrossRef]
21. Philipps, S. Photovoltaics Report. Fraunhofer ISE. Freiburg, Germany. 2025. Available online: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html (accessed on 18 November 2025).
22. Wambach, K.; Libby, C.; Shaw, S. Literature Review and Update to Empirical LCI Data and Patent Review, International Energy Agency—Photovoltaics Power Systems Program. 2024. Available online: https://iea-pvps.org/key-topics/advances-in-module-recycling-literature-review-and-update-to-empirical-lci-data-and-patent-review/ (accessed on 22 November 2025).
23. Chowdhury, H.; Chang, N.L.; Song, S.; Xie, Z.; Zuo, J.; Shen, Y. Life cycle assessment and techno-economic analysis of a laser-based end-of-life solar panel recycling process. *Sol. Energy Mater. Sol. Cells* **2026**, *302*, 114358. [CrossRef]
24. Granata, G.; Altimari, P.; Pagnanelli, F.; De Greef, J. Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective. *J. Clean. Prod.* **2022**, *363*, 132384. [CrossRef]
25. Dias, P.R.; Schmidt, L.; Chang, N.L.; Lunardi, M.M.; Deng, R.; Trigger, B.; Gomes, L.B.; Egan, R.; Veit, H. High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112900. [CrossRef]
26. Song, G.; Lu, Y.; Liu, B.; Duan, H.; Feng, H.; Liu, G. Photovoltaic panel waste assessment and embodied material flows in China, 2000–2050. *J. Environ. Manag.* **2023**, *338*, 117675. [CrossRef] [PubMed]
27. Cucchiella, F.; D'Adamo, I.; Rosa, P. End-of-Life of used photovoltaic modules: A financial analysis. *Renew. Sustain. Energy Rev.* **2015**, *47*, 552–561. [CrossRef]
28. Mahmoudi, S.; Huda, N.; Behnia, M. Environmental impacts and economic feasibility of end of life photovoltaic panels in Australia: A comprehensive assessment. *J. Clean. Prod.* **2020**, *260*, 120996. [CrossRef]
29. Aninat, R.; van der Vleuten, M.; Scraigne, J.; Fledderus, H.; Biezemans, A.; Bosman, J.; Gomes, J.; Kuypers, A.; Theelen, M. Laser-Assisted Delamination for High-Value Recycling of Solar Panels. *Prog. Photovolt. Res. Appl.* **2026**, *34*, 297–309. [CrossRef]
30. Gmbh, F.L.A.X.R.E.S. FLAXTHOR®: Solar Modules Are Exposed to a Very Short, High-Intensity Light Pulse for Delamination in Our Large-Scale Flashing Unit, Solar Impulse Foundation. 2025. Available online: https://solarimpulse.com/solutions-explorer/flaxthor-r (accessed on 9 December 2025).
31. Mulazzani, A.; Eleftheriadis, P.; Leva, S. Recycling c-Si PV Modules: A Review, a Proposed Energy Model and a Manufacturing Comparison. *Energies* **2022**, *15*, 8419. [CrossRef]
32. He, W.; Zhao, Z.; Yuan, J.; Xiao, F. Recent development of ethylene–vinyl acetate modified asphalt. *Constr. Build. Mater.* **2023**, *363*, 129800. [CrossRef]
33. Chung, J.; Seo, B.; Lee, J.; Kim, J.Y. Comparative analysis of I2-KI and HNO_3 leaching in a life cycle perspective: Towards sustainable recycling of end-of-life c-Si PV panel. *J. Hazard. Mater.* **2021**, *404*, 123989. [CrossRef] [PubMed]
34. Lee, S.-H.; Jang, Y.-C. Analysis for End-of-Life Solar Panel Generations by Renewable Energy Supply towards Carbon Neutrality in South Korea. *Energies* **2023**, *16*, 8039. [CrossRef]
35. Liu, B.; Li, M.; Chen, J.; Sun, Z. Projected waste and recycling potential of Chinas photovoltaic industry. *Waste Manag.* **2025**, *191*, 264–273. [CrossRef] [PubMed]
36. Zion Market Research. Glass Recycling Market. 2023. Available online: https://www.zionmarketresearch.com/report/glass-recycling-market (accessed on 26 September 2025).
37. Mordor Intelligence. Global Aluminium Recycling Market. 2025. Available online: https://www.mordorintelligence.com/industry-reports/aluminum-recycling-market (accessed on 26 September 2025).
38. Grand View Research. Silicon Wafer Reclaim Market (2025–2030). 2025. Available online: https://www.grandviewresearch.com/industry-analysis/silicon-wafer-reclaim-market (accessed on 26 September 2025).
39. Data Insights Market Silver Recycling 2025 to Grow at 4.1 CAGR with 4283 Million Market Size: Analysis and Forecasts 2033. Available online: https://www.datainsightsmarket.com/reports/silver-recycling-1113819 (accessed on 26 September 2025).
40. Grand View Research. Copper Market (2025–2030). 2025. Available online: https://www.grandviewresearch.com/industry-analysis/copper-market-report (accessed on 26 September 2025).
41. Business Analytiq. Glass Cullet Price Index: Summary of Recent Glass Cullet Price Developments. 2025. Available online: https://businessanalytiq.com/procurementanalytics/index/cullet-price-index/ (accessed on 2 October 2025).
42. Alfred University. Next Generation Glass Processing, Collection and Recycling, Inamori School of Engineering, New York State College of Ceramics at Alfred University. 2023. Available online: https://dec.ny.gov/sites/default/files/2023-12/glassrecyclingreport.pdf (accessed on 2 October 2025).
43. EU Recycle. Scrap Metal Prices in the UK & European Countries. 2025. Available online: https://www.eurecycleinfo.com/scrap-metal-prices (accessed on 2 October 2025).
44. Sigworth, G.K. Refining of Secondary Aluminum: Important Chemical Factors. *JOM* **2021**, *73*, 2594–2602. [CrossRef]

45. Bernreuter Research. Polysilicon Market Reports: Polysilicon Price Trends. 2025. Available online: https://www.bernreuter.com/polysilicon/price-trend/ (accessed on 2 October 2025).
46. Live Price of Gold. Silver Price in Scrap. 2025. Available online: https://www.livepriceofgold.com/silver-price/scrap.html (accessed on 2 October 2025).
47. Westmetall. Market Data: Copper. 2025. Available online: https://www.westmetall.com/en/markdaten.php?action=table&field=LME_Cu_cash (accessed on 2 October 2025).
48. Morell, J.; Ribas, D.; Guimerà, X.; Mena, S.; Guirado, G.; Dorado, A.D. Direct Copper Electrowinning from E-Waste Leachates Containing High Ferrous Ion Concentrations. *SSRN* **2025**, *47*. [CrossRef]
49. Ovaitt, S.; Mirletz, H.; Seetharaman, S.; Barnes, T. PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts. *iScience* **2022**, *25*, 103488. [CrossRef] [PubMed]
50. DaDamo, I.; Ferella, F.; Gastaldi, M.; Ippolito, N.M.; Rosa, P. Circular solar: Evaluating the profitability of a photovoltaic panel recycling plant. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2023**, *41*, 1144–1154. [CrossRef] [PubMed]
51. Shanghai Metal Market (SMM). Silver Paste Consumption Declines, Growth in Silver Consumption for PV May Slow Down. 2025. Available online: https://www.metal.com/en/newscontent/103545216 (accessed on 10 October 2025).
52. Bonakdarpour, M.; Bailey, T. The Future of Copper: Will the Looming Supply Gap Short-Circuit the Energy Transition?, S&P Global. 2022. Available online: https://cdn.ihsmarkit.com/www/pdf/0722/The-Future-of-Copper_Full-Report_14July2022.pdf (accessed on 14 December 2025).
53. Sah, D.; Kumar, S. Recovery and analysis of valuable materials from a discarded crystalline silicon solar module. *Sol. Energy Mater. Sol. Cells* **2022**, *246*, 111908. [CrossRef]
54. Trading Economics Lead. 2025. Available online: https://tradingeconomics.com/commodity/lead (accessed on 2 October 2025).
55. The London Metal Exchange Tin. 2025. Available online: https://www.lme.com/en/metals/non-ferrous/lme-tin (accessed on 2 October 2025).
56. Business Analytiq Ethylene Vinyl Acetate (EVA) Price Index. 2025. Available online: https://businessanalytiq.com/procurementanalytics/index/ethylene-vinyl-acetate-eva-price-index/ (accessed on 2 October 2025).
57. Alibaba. Transparent Solar Module Back Sheet of Solar Panel Raw Material Solar Pv Backsheet for Solar Module Lamination. 2025. Available online: https://www.alibaba.com/product-detail/Transparent-Solar-Module-Back-Sheet-of_1601487378766.html?spm=a2700.7724857.0.0.b8ff7e24cP9jt3 (accessed on 2 October 2025).
58. Nold, S.; Mittag, M.; Goraya, B.; Subasi, D.; Rentsch, J.; Preu, R.; Neuhaus, H. Reshoring Solar Module Manufacturing to Europe: A Cost Gap Analysis and Policy Impact Simulation, Fraunhofer ISE. 2025. Available online: https://api.solarpowereurope.org/uploads/SPE_Reshoring_Solar_Manufacturing_to_Europe_Report_Sep_2025_6b1a0ad5da.pdf (accessed on 3 January 2026).
59. European Commission. General Guide for Life Cycle Assessment: Provisions and Action Steps, Italy. 2010. Available online: https://op.europa.eu/en/publication-detail/-/publication/a47e524c-acc4-4a27-98d7-78211e6aa59b/language-en (accessed on 18 December 2025).
60. Evans, M.-A.; Grand, P.-P.; Dupuis, J. Diversifying the solar photovoltaic supply chain to secure Europes energy and climate roadmap and sovereignty. *iScience* **2025**, *28*, 112751. [CrossRef] [PubMed]
61. Basore, P.; Feldman, D. *Solar Photovoltaics: Supply Chain Deep Dive Assessment*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2022. [CrossRef] [PubMed]
62. Helveston, J.P.; He, G.; Davidson, M.R. Author Correction: Quantifying the cost savings of global solar photovoltaic supply chains. *Nature* **2023**, *618*, E24. [CrossRef] [PubMed]
63. Latunussa, C.E.L.; Mancini, L.; Blengini, G.A.; Ardente, F.; Pennington, D. *Analysis of Material Recovery from Silicon Photovoltaic Panels: Life Cycle Assessment and Implications for Critical Raw Materials and Ecodesign*; EUR 27797; Publications Office of the European Union: Luxembourg, 2016. [CrossRef]
64. Espinosa, N.; Bobba, S.; Latunussa, C.E.L.; Leccisi, E. Assessing Photovoltaic Recycling Capacities and Policy Gaps in the European Union. *Adv. Energy Sustain. Res.* **2026**. *Early View*. [CrossRef]
65. Sharma, A.; Pandey, S.; Kolhe, M. Global review of policies & guidelines for recycling of solar PV modules. *Int. J. Smart Grid Clean Energy* **2019**, *8*, 597–610. [CrossRef]
66. El-Khawad, L.; Bartkowiak, D.; Kümmerer, K. Improving the end-of-life management of solar panels in Germany. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112678. [CrossRef]
67. Papamichael, I.; Zorpas, A.A. End-of-waste criteria in the framework of end-of-life PV panels concerning circular economy strategy. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2022**, *40*, 1677–1679. [CrossRef]
68. Predoiu, R.L. A Sustainable Approach for Managing the End-of-Life Phase of Photovoltaic Systems. Ph.D. Thesis, Technische Universität Wien, Vienna, Austria, 2017. [CrossRef]
69. Salim, H.K.; Stewart, R.A.; Sahin, O.; Dudley, M. Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review. *J. Clean. Prod.* **2019**, *211*, 537–554. [CrossRef]

70. Ding, N.; Zhang, Z.; Yang, J.; Li, X.; Sun, S.; Zhao, S. Implications for PV module ecodesign from a life cycle perspective under the framework of the EU ecodesign sustainable products regulation. *Renew. Sustain. Energy Rev.* **2026**, *226*, 116325. [CrossRef]
71. Fraunhofer ISE. Installed Capacity of Variable Renewables (VRE) for Electricity Generation in Germany. 2024. Available online: https://energy-charts.info/charts/remod_installed_power_2024/chart.htm?l=en&c=DE&source=renewable&charttype=column&stacking=stacked_grouped (accessed on 2 September 2025).
72. Secondsol. Solara SM2000-24 100 Wp. 2025. Available online: https://www.secondsol.com/en/anzeige/6219/zonnepanelen/kristallijn/poly/solara/sm2000-24 (accessed on 14 June 2025).
73. Secondsol. Tenesol TE2000 200Wp 200 Wp. 2025. Available online: https://www.secondsol.com/en/anzeige/12003/solar-panel/crystalline/poly/tenesol/te2000-200wp (accessed on 14 June 2025).
74. Secondsol. Tenesol TE2000 210Wp 20P1-A1 210 Wp. 2025. Available online: https://www.secondsol.com/en/anzeige/4612/solar-panel/crystalline/mono/tenesol/te2000-210wp-20p1-a1 (accessed on 14 June 2025).
75. ENF Solar. E-2000. 2025. Available online: https://www.enfsolar.com/pv/panel-datasheet/crystalline/27563 (accessed on 14 June 2025).
76. ENF Solar. Mono-340W–360W. 2025. Available online: https://www.enfsolar.com/pv/panel-datasheet/crystalline/39393 (accessed on 14 June 2025).
77. Toms Car HiFi. Jinko Solar—Tiger Neo N-Type mit 440 W. Toms-Car-Hifi—Kaufen Was Freu(n)de Macht! 2025. Available online: https://www.toms-car-hifi.de/technikwelt/freizeit/solar/pv-module/51862/tiger-neo-n-type-mit-440-w?sPartner=guenstiger (accessed on 14 June 2025).
78. Bilitewski, B.; Wagner, J.; Reichenbach, J. Best Practice Municipal Waste Management: Information Pool on Approaches Towards a Sustainable Design of Municipal Waste Management and Supporting Technologies and Equipment, Umwelt Bundesamt. 2018. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-05-30_texte_40-2018-municipal-waste-management_en.pdf (accessed on 12 December 2025).
79. Langan, L.; Tully, J. Construction Cost Guide, Buildcost Chartered Quantity Surveyors. 2024. Available online: https://buildcost.ie/wp-content/uploads/2024/11/Buildcost-Construction-Cost-Guide-2nd-Half-2024_compressed.pdf (accessed on 12 December 2025).
80. Yu, L. Recycling End-of-Life Silicon PV Panel with Molten Salt Bath: Degree Project in Sustainable Energy Engineering. Master's Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2023. Available online: https://www.diva-portal.org/smash/get/diva2:1797566/FULLTEXT01.pdf (accessed on 12 February 2025).
81. Wand, R.; Leuthold, F. Feed-in tariffs for photovoltaics: Learning by doing in Germany? *Appl. Energy* **2011**, *88*, 4387–4399. [CrossRef]
82. Taoxia. How Much Is the Crystal Growing Furnace Price in 2025: Cost Guide. 2025. Available online: https://www.taoxiaintelli.com/crystal-growing-furnace-price/ (accessed on 28 November 2025).
83. Chauhan, A.; Saini, R. Techno-economic feasibility study on Integrated Renewable Energy System for an isolated community of India. *Renew. Sustain. Energy Rev.* **2016**, *59*, 388–405. [CrossRef]
84. Imre-Lucaci, Á.; Imre-Lucaci, F.; Fogarasi, S. Modeling, Simulation, and Techno-Economic Assessment of a Spent Li-Ion Battery Recycling Plant. *Materials* **2025**, *18*, 3715. [CrossRef] [PubMed]
85. Hannula, P.-M.; Khalid, M.K.; Janas, D.; Yliniemi, K.; Lundström, M. Energy efficient copper electrowinning and direct deposition on carbon nanotube film from industrial wastewaters. *J. Clean. Prod.* **2019**, *207*, 1033–1039. [CrossRef]
86. Bundesagentur. Strommarktdaten (SMARD): Industrial Electricity Price Trends. 2025. Available online: https://www.smard.de/page/en/topic-article/5892/216044/industrial-electricity-price-trends (accessed on 24 October 2025).
87. Schmied, M.; Knörr, W. Calculating GHG Emissions for Freight Forwarding and Logistics Services in Accordance with EN 16258: Terms, Methods, Examples, European Association for Forwarding, Transport, Logistics and Customs Services. 2012. Available online: https://www.clecat.org/media/CLECAT_Guide_on_Calculating_GHG_emissions_for_freight_forwarding_and_logistics_services.pdf (accessed on 10 September 2025).
88. Benzinpreis Aktuell. Benzinpreise Aktuell. 2025. Available online: https://www.benzinpreis-aktuell.de/ (accessed on 1 October 2025).
89. Schmidt, M.; Singh, B. Selectively closing recycling centers in Bavaria: Reforming waste-management policy to reduce disparity. *Networks* **2024**, *84*, 148–160. [CrossRef]
90. Hestin, M.; de Veron, S.; Burgos, S. Economic Study on Recycling of Building Glass in Europe, Deloitte. 2016. Available online: https://www.glassforeurope.com/wp-content/uploads/2018/04/Economic-study-on-recycling-of-building-glass-in-Europe-Deloitte.pdf (accessed on 9 December 2025).
91. Fick, G. Technical Report: Market Development for Secondary Casting Alloys Beyond Motor Blocks—Study on Casting Alloy Market and Recycling, Institut de Recherche Technologique IRT_M2P_2022.05.001_IAI_TR_20230504. 2023. Available online: https://international-aluminium.org/wp-content/uploads/2023/07/IRT_M2P_Market-Development-for-2ary-Casting-Alloys-beyond-Motor-Blocks_final.pdf (accessed on 9 December 2025).

92. Dierks, C.; Hagedorn, T.; Mack, T.; Zeller, V. Consequential life cycle assessment of demolition waste management in Germany. *Front. Sustain.* **2024**, *5*, 1417637. [CrossRef]
93. Salary Expert. Heavy Truck Driver: Average Salaries. 2025. Available online: https://www.salaryexpert.com/salary/job/heavy-truck-driver/germany (accessed on 9 December 2025).
94. Comité National Routier (CNR). Operating Conditions and Costs Excluding Overhead Costs, for a 40-Tonne HGV, Operated on Long Distance International Routes: 2021 Values. 2021. Available online: https://www.cnr.fr/en/detail-pays/2 (accessed on 2 December 2025).
95. Toll Collect Gmbh. Toll Rates: Composition of the Toll Rates. 2025. Available online: https://www.toll-collect.de/en/toll_collect/bezahlen/maut_tarife/p1745_mauttarife_07_2024.html (accessed on 11 December 2025).
96. Qingdao Longshore Chemicals Co., Ltd. Sodium-Hydroxide Market Price Naoh Flakes, Solid Caustic-Soda Price Per Ton Online Sale. 2025. Available online: https://longshores.en.made-in-china.com/product/cnWpzUErmQYw/China-Sodium-Hydroxide-Market-Price-Naoh-Flakes-Solid-Caustic-Soda-Price-Per-Ton-Online-Sale.html (accessed on 2 October 2025).
97. Boqi Chemicals Shanghai Ltd. Liquid Solid Flake 90% Price KOH Potassium Hydroxide. 2025. Available online: https://boqichem.en.made-in-china.com/product/mERUKgzymLpQ/China-1310-58-3-Liquid-Solid-Flake-90-Price-KOH-Potassium-Hydroxide-for-Sale.html?pv_id=1j6laveuua51&faw_id=1j6lavu1ia8d&bv_id=1j6lavu1rbb&pbv_id=1j6lave040b6g (accessed on 2 October 2025).
98. Statistisches Bundesamt. Average Hourly Wage of Persons Employed. 2025. Available online: https://www.destatis.de/EN/Themes/Labour/Labour-Market/Quality-Employment/Dimension2/2_5_HourlyEarnings.html (accessed on 14 December 2025).

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