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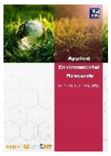

Research Article

Comparative Life Cycle Assessment of End-of-Life Crystal Silicon Photovoltaic Panels: Recovery Methods and Extended Life in Agricultural Application

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Abstract

The increasing deployment of crystalline silicon (c-Si) photovoltaic (PV) panels has raised concerns about their waste management. This study evaluated management strategies for discarded c-Si PV panels in Thailand, integrating environmental and economic analyses. Life cycle assessment (LCA) and cost-effectiveness analysis (CEA) were applied. The LCA can be divided into 2 parts: (1) secured landfill vs decentralized recycling by existing facilities vs centralized full recovery and (2) reusing PV panels in agricultural applications. The results revealed that secured landfills were the most environmentally burdensome (34.43 Pt), whereas centralized recycling achieved net benefits (-211.93 Pt) through emission reductions and recovery of silver, copper, and silicon. The CEA confirmed the viability of the integrated reuse-recycling systems. The integration of reusing PV panels in agriculture with recycling systems by CEA was viable.

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Introduction

The rapid global expansion of photovoltaic (PV) technology plays a critical role in decarbonizing the energy sector and achieving international renewable energy and climate mitigation targets. The crystalline silicon (c-Si) PV panels, which dominate the global market, are expected to contribute significantly to low-carbon electricity generation in the coming decades.

Inappropriate disposal practices, particularly landfilling, remain prevalent in countries with limited recycling infrastructure. These methods present considerable environmental risks due to the presence of hazardous substances such as lead (Pb) and cadmium (Cd), which can leach into soil and groundwater (Fthenakis et al., 2008).

The life cycle assessment (LCA) offers a comprehensive and standardized methodology for evaluating the environmental performance of products and processes across all life cycle stages from raw material extraction to disposal.

Over the past decade, LCA research has increasingly focused on practical end-of-life (EOL) treatment options for discarded c-Si PV panels, as presented in Table S1. Studies have assessed the environmental trade-offs of different recovery processes, including thermal, chemical, and mechanical methods, highlighting the balance between resource recovery, process efficiency, and ecological impact (Ansanelli et al., 2021; Chung et al., 2021; Maani et al., 2020).

In parallel, the recovery of high-value and scarce materials, especially silicon, has become a central research focus (Fthenakis et al., 2008; Yamashita et al., 2004). Although recycling has been explored extensively in countries such as Japan, Germany, and the United States (Palitzsch and Loser, 2012), challenges remain due to high processing costs, evolving panel designs, and declining material content (Riech et al., 2021; Mahmoudi et al., 2019a; Kim and Jeong, 2016).

Recent developments in countries such as China, South Korea, Mexico, and the Netherlands illustrate emerging interest in integrated recycling systems that combine mechanical, thermal, and chemical treatments (Chowdhury et al., 2020; Mahmoudi et al., 2019a; Tao and Yu, 2015). In Thailand, preliminary efforts have focused on adapting existing e-waste infrastructure (factory type 106) for PV recycling (Department of Alternative Energy Development and Efficiency, 2019), although these efforts remain at the laboratory scale. In light of these trends, national and regional initiatives are increasingly seeking to implement closed-loop recycling systems capable of reintegrating recovered materials into new PV production cycles (Farrell et al., 2020).

This study aims to contribute to the development of a sustainable and context-specific EOL management framework for discarded PV panels in Thailand. Specifically, it evaluates the environmental impacts of alternative treatment scenarios via LCA and examines their cost-effectiveness via cost-effectiveness analysis (CEA). Three waste management approaches, namely, Landfill, decentralization, and centralization, were evaluated. The integration of the reused PV panel was investigated.

Materials and methods

This study adopts a mixed-methods approach to develop a sustainable discarded PV panel management framework in Thailand. The methodology integrates the quantitative environment via LCA and economic assessments via cost-effectiveness (CE) analysis.

1) Life cycle assessment of EOL management of discarded PV panels: Conceptual approach

The scenarios used in LCA were developed on the basis of a comprehensive literature review (Department of Primary Industries and Mines, Ministry of Industry, 2023; Faircloth et al., 2019; Latunussa et al., 2016; Department of Industrial Works, Ministry of Industry, 2014). This study specifically focuses on c-Si PV panels, which represent the predominant PV technology in current use. Three distinct EOL scenarios were assessed: (1) landfill, (2) decentralization, and (3) centralization. In addition to these conventional waste management approaches, an extended shelf-life strategy was incorporated, wherein decommissioned PV panels are repurposed for secondary use in agricultural applications prior to entering one of the mentioned EOL pathways. The analysis compares the environmental impacts of each scenario and identifies environmental hotspots to inform sustainable decision-making in discarded PV management.

The baseline scenario in the LCA involved the secure landfilling of EOL PV panels. Prior to disposal, the aluminum frames and junction boxes were manually removed from the discarded c-Si panels, after which the remaining laminate materials and cells inside were directed to a secure landfill facility.

2) LCA application

This study aims to compare the environmental impacts of the proposed discarded PV panel management scenarios in Thailand. The objective is to identify the most effective options for policymakers to support sustainable waste management strategies. The functional unit (FU) provides a consistent basis for comparison and was defined as 1,000 kg of discarded c-Si PV panels. System boundaries span collection, transportation, and final disposal/recycling, excluding upstream manufacturing and use phases to isolate EOL impacts.

By prioritizing processes with the highest environmental burdens, this study directly supports Thailand’s transition to circular economy practices in renewable energy infrastructure.

The system boundary in LCA studies defines the scope of the analysis, encompassing the specific unit processes under investigation. This boundary must be meticulously defined and justified, aligning with the study's objectives and scope. Establishing the system boundary involves a thorough characterization of the system.

The system boundary of this study was defined as the EOL stage, adopting a “gate-to-grave” approach, as illustrated in Figure 1(B). Specifically, the scope of this LCA begins from the decommissioning of PV solar farms and extends through three proposed EOL management scenarios, as detailed in the following section. In addition, the reuse of discarded PV panels in agricultural water pumping systems was also examined as a supplementary strategy to enhance environmental performance.

3) Scenario description

The scenarios are divided into 2 main parts, as shown in Figure 2.

The first part, “Part 1,” consists of 3 scenarios:

Scenario 1: Secured landfill (Landfill)

After decommissioning and dismantling, discarded PV panels are transported from solar farms to the nearest factory type 106. Then, the junction boxes and aluminum frames were removed, and the remaining frames (including glass, silicon wafers, bus bars, and backsheets) were transported to secured landfills. The secured landfills in this study are located in Ratchaburi, Phetchabun, Saraburi, Sa Kaew, and Chonburi Provinces (Department of Industrial Works, Ministry of Industry, 2014). The details of the inputs and outputs in Landfill are described in Figure 3(A).

Scenario 2: Decentralized recycling by existing recycling facilities (Decentralization)

After decommissioning and dismantling, discarded PV panels are transported from solar farms to the nearest factory type 106. The junction boxes and aluminum frames were subsequently removed, and the remaining frames (including glass, silicon wafers, bus bars, and backsheets) were transported to the nearest e-waste recycling facilities (>1,000 HP). Waste from the recycling process was transported to secured landfills. The details of the inputs and outputs in decentralization are described in Figure 3(B) and Figure 4.

Scenario 3: Centralized recycling by the new full recovery facility (Centralization)

After decommissioning and dismantling, discarded PV panels were transported from the solar farms to the collection points. The discarded PV panels were subsequently transported from collection points to a new recycling facility expected to be established in Saraburi Province for full recovery of discarded PV panels. Waste from the recycling process was transported to secured landfills. The details of the inputs and outputs in Centralization are described in Figure 5.

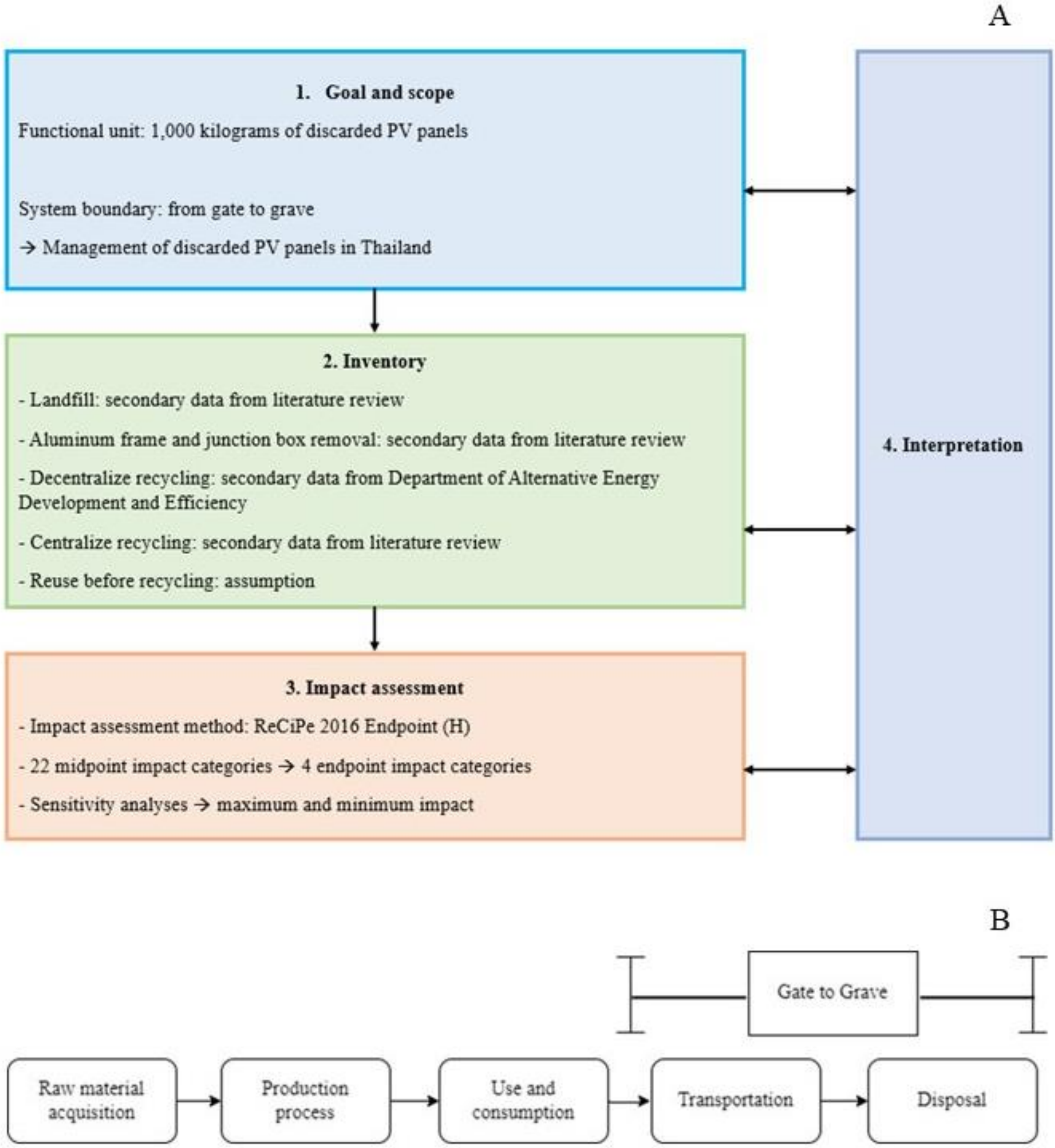

Figure 1 A: Methodological Framework of LCA and B: System boundary (Gate to Grave).

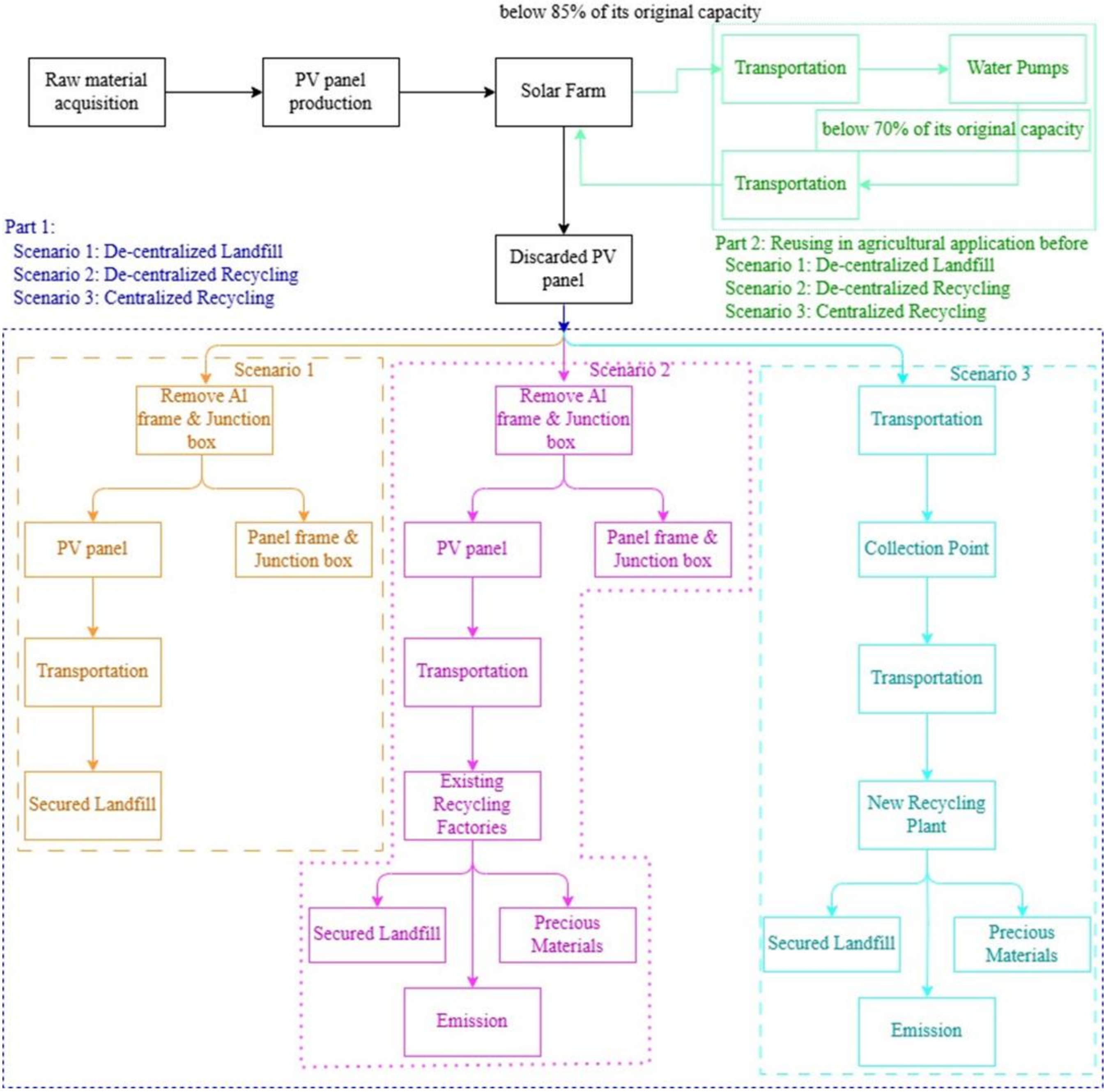

Fig. 2. Drafted scenario flowchart.

In the second part, "Part 2: Reusing PV panels in agricultural applications before entering other waste management in Scenarios 1–3 (Reusing PV panels)", the environmental impact of reusing discarded PV panels with the assumption of 85% efficiency in the agricultural sector was assessed. After being repurposed for agricultural use for a duration of five years, the panels were then processed through the same three EOL scenarios described in Part 1. The assumed efficiency cutoff and reuse duration were based on interview data obtained from a solar farm company operating similar reuse projects.

The distance from solar farms to the nearest factory type 106, the distance from factory type 106 to nearest e-waste recycling facilities with a capacity greater than 1,000 HP, and the average distance from factory type 106 to secured landfills are based on the average distance derived and calculated from the locations on the map in Figure S1 (Department of Industrial Works, Ministry of Industry, 2014). The distance from solar farms to collection points and the distance from collection points to the full recovery factory for discarded PV panels are derived from the literature review (Latunussa et al., 2016).

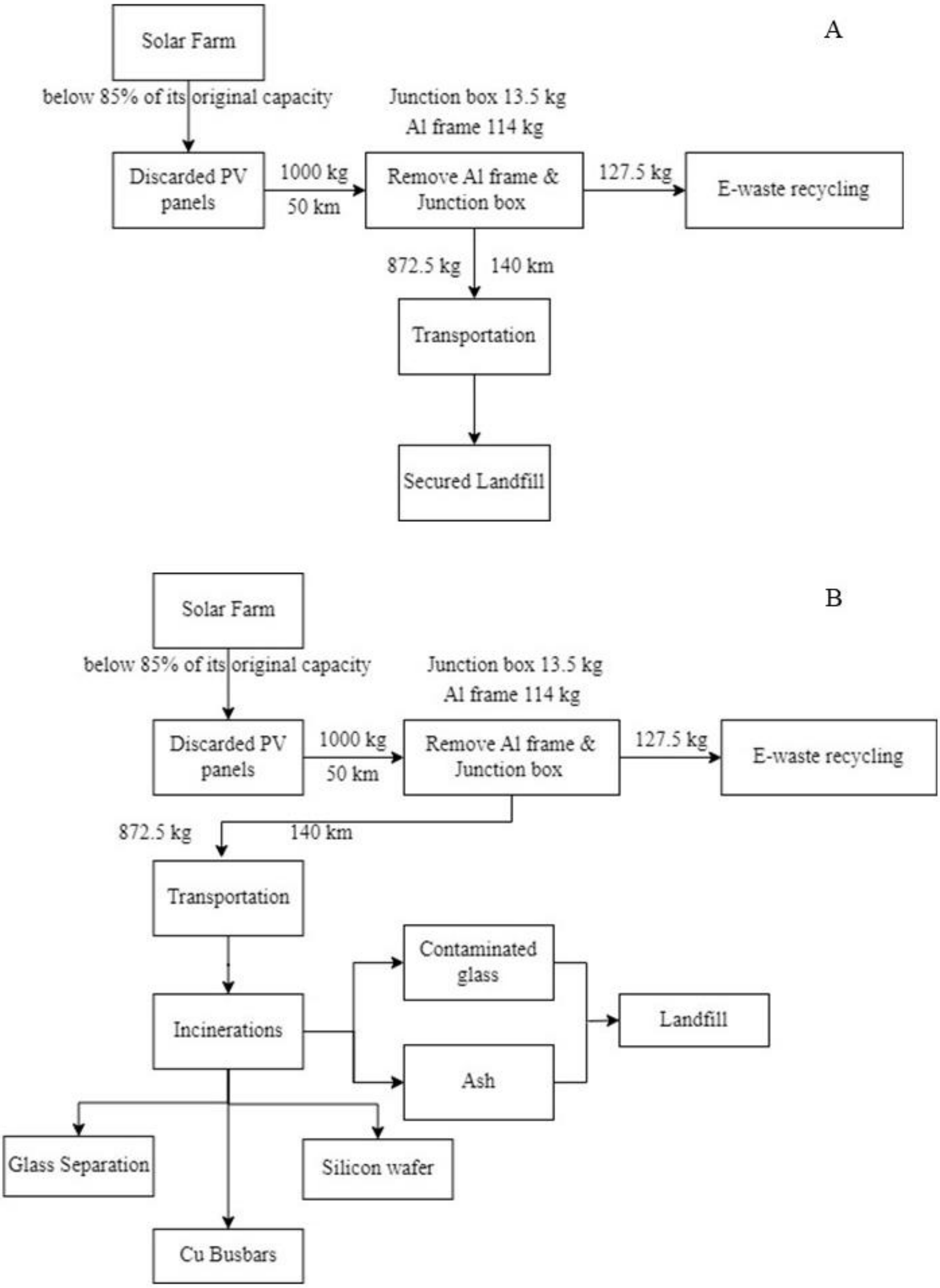

Figure 3 Draft scenario flow charts A: Landfill and B: Decentralization.

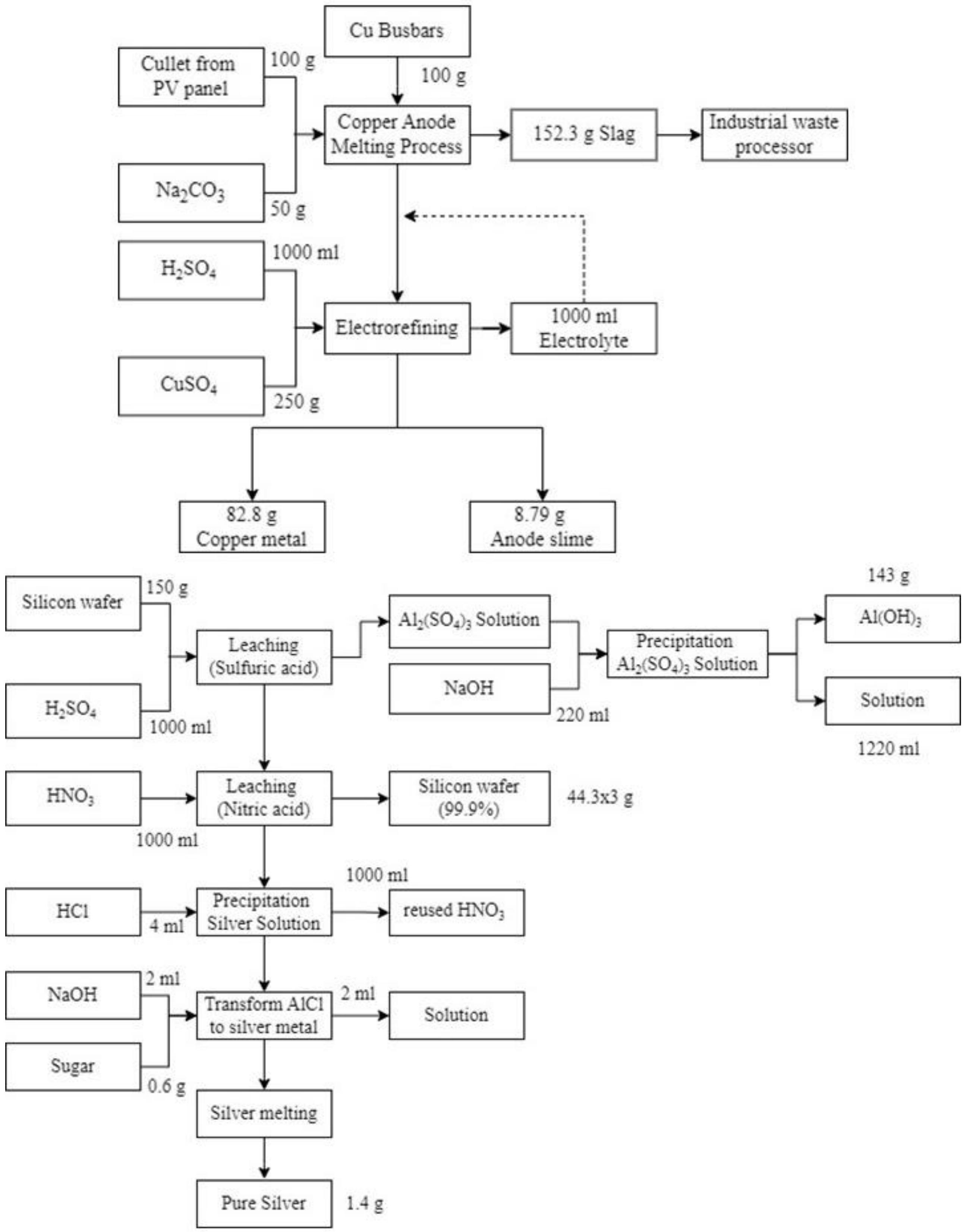

Figure 4 Details in decentralization.

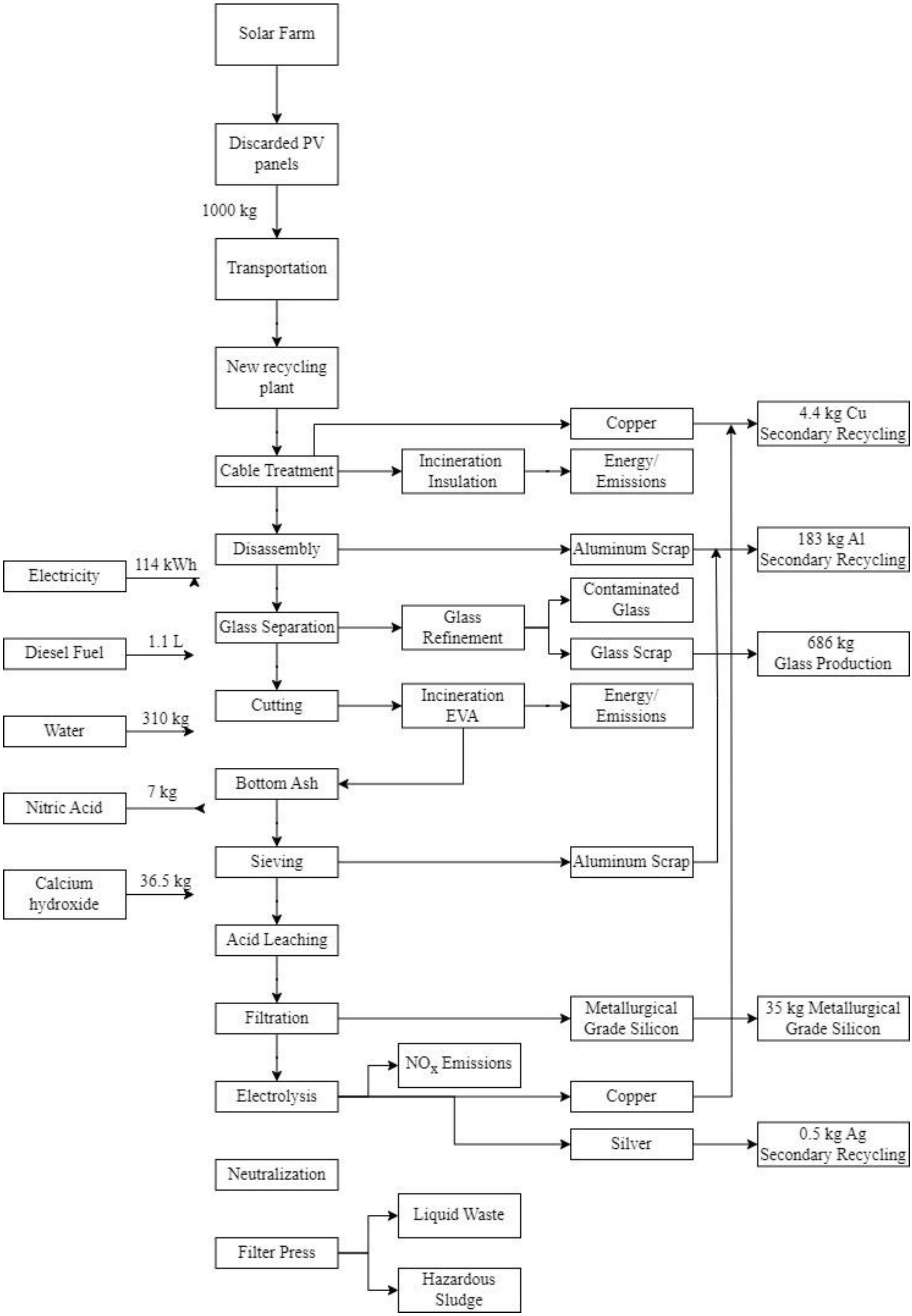

Figure 5 System boundaries of centralization.

4) Life cycle inventory (LCI)

The LCI data was compiled through a combination of the literature review in Table 1 and calculations to quantify the relevant inputs, outputs, and emissions associated with discarded PV panel management processes.

In Landfill, data on input resources and output flows are sourced from the Department of Primary Industries and Mines (Department of Primary Industries and Mines, Ministry of Industry, 2023), whereas emission factors are obtained from the Ecoinvent database via SimaPro software (Ecoinvent, 2020).

For decentralization, estimates of material and energy consumption were derived on the basis of assumptions informed by relevant literature sources (Department of Primary Industries and Mines, Ministry of Industry, 2023; Ecoinvent, 2020).

In Central China, all inventory data were adopted from previous studies (Faircloth et al., 2019; Latunussa et al, 2016)

Additionally, inventory data related to the reuse of PV panels were based on assumptions and the Eco-invent database (Ecoinvent, 2020). The LCI analysis was conducted via SimaPro version 9.0.0.35 in conjunction with the Ecoinvent database to ensure consistency and comparability across scenarios.

The life cycle inventory for the three scenarios, i.e., landfill, decentralization, and centralization, is based on the functional unit of 1,000 kg of discarded c-Si PV panels. An overview of the inventory data required for the life cycle assessment is presented in Table S2. Detailed inventory data and their sources are provided separately for each scenario in Table S3 for Landfill, Table S4 for decentralization, and Table S5 for centralization.

The midpoint impact categories together with the related environmental impact indicators are shown in Table S6. The transportation and distribution data are reported in Table S7 for landfill, Table S10 for decentralization, and Table S13 for centralization. The quantities of valuable and valuable materials recovered or lost in landfill are presented in Table S8.

The comprehensive life cycle inventory data for each stage are provided below. The disposal stage for the landfill is described in Table S9. The recycling and disposal stages for decentralization are presented in Tables S11 and S12. The transportation, recycling, and disposal stages for centralization are shown in Tables S13, S14, and S15, respectively.

A summary of all inventory data sources associated with the reuse of PV panels before the three main EOL scenarios are considered is provided in Table S16. The life cycle inventory data for the transportation stage of the reused PV panel is shown in Table S17, and the use stage data is presented in Table S18. Finally, the datasets obtained from the Ecoinvent 3, USLCI, and ELCD databases were used to collect inventory and environmental impact data for all the scenarios listed in Table S19.

5) Life cycle impact assessment (LCIA)

The environmental impacts in this study were assessed via the ReCiPe 2016 method, which employs both the midpoint (H) and endpoint (H) approaches. ReCiPe 2016 is widely recognized and frequently applied in LCA studies focused on the management of discarded c-Si PV panels (Adiansyah et al, 2025; Duan et al., 2025; Li et al., 2025; Lisperguer et al. 2020; Ardente et al., 2019; Huijbregts et al., 2017).

6) Cost-effective analysis

A cost-effectiveness (CE) analysis was conducted to assess and compare the economic and environmental performance of alternative management scenarios for discarded c-Si PV panels in Thailand. The analysis employed a CE ratio defined as the cost (C, in US dollars or USD) per unit of environmental impact (E, in Pt), calculated as CE = C/E, where lower values indicate greater cost effectiveness in reducing the environmental burden per unit cost.

The CE assessment followed a four-step methodo-logical framework: (1) collection of cost data for each scenario; (2) quantification of environmental impacts via LCA endpoint single scores (expressed in Pt); (3) calculation of CE ratios; and (4) identification of the most efficient scenario on the basis of the lowest CE value.

The cost components considered in the analysis included recycling service fees, secured landfill charges, and operational expenses (Department of Primary Indus-tries and Mines, Ministry of Industry, 2023; Faircloth et al., 2019; Latunussa et al., 2016). The economic value recovered from materials, such as aluminum, silicon, glass, silver, copper, and junction boxes, was estimated via market prices obtained from Thai governmental sources (Department of Primary Indus-tries and Mines, Ministry of Industry, 2023).

Table 1 Life cycle inventory of 3 scenarios (functional unit: 1,000 kg discarded c-Si PV panels)

Landfill		Decentralization		Centralization	
Input					
Lorry 3.5-7.5 (ton.km)	172.15	Lorry 3.5-7.5 (ton.km)	327.66	Lorry 3.5-7.5 (ton.km)	102.08
Aluminum frame (kg)	114.00	Aluminum frame (kg)	114.00	Lorry 7.5 - 16 (ton.km)	150.00
Junction box and cable (kg)	13.50	Junction box and cable (kg)	13.50	PV panel (kg)	1,000.00
PV cells (kg)	872.50	PV cells (kg)	872.50	Calcium hydroxide (kg)	36.50
		Na_2CO_3 (kg)	3.65	Nitric acid (kg)	7.00
		H_2SO_4 (L)	215.70	Water (kg)	310.00
		$CuSO_4$ (kg)	18.25	Diesel Fuel (L)	1.10
		HNO_3 (L)	142.70	Electricity consumption (kWh)	114.00
		HCl (L)	0.57		
		NaOH (L)	0.29		
		Sugar (kg)	0.09		
		Electricity consumption (kWh)	62.50		
Outputs					
Aluminum scrap (kg)	114.00	Aluminum scrap (kg)	114.00	Aluminum scrap (kg)	183.00
PVC (incineration) (kg)	12.50	PVC (incineration) (kg)	12.50	Glass (kg)	686.00
Copper (kg)	1.00	Copper (kg)	1.00	Copper (kg)	4.40
PV cells (kg)	872.50	Glass (kg)	511.50	Silicon (kg)	35.00
		Silicon (kg)	18.96	Silver (kg)	0.50
		Silver (kg)	0.23		
		Copper (kg)	6.04		
		Aluminum hydroxide (kg)	20.40		
		Anode slime (kg)	0.64		
		Wastewater (kg)	40.53		
		Solid waste (kg)	91.20		

Results and discussion

1) Comparative EOL management approach

The comparative LCIA results for the three proposed scenarios of discarded PV panel management are visualized in Figure 6(A). A comparison of the three scenarios based on midpoint indicators is summarized in Table S26, while the corresponding endpoint comparison is presented in Table S27.

The life cycle impact assessment results for Landfill are presented in Table S20 for the midpoint indicators and in Table S21 for the endpoint indicators. The opportunity loss of the precious materials in Landfill is shown in Table S28 for the midpoint indicators and in Table S29 for the endpoint indicators. The results for decentralization are shown in Table S22 for the midpoint indicators and in Table S23 for the endpoint indicators. The results for centralization are provided in Table S24 for the midpoint indicators and in Table S25 for the endpoint indicators.

Compared with the other scenarios, decentralization had significantly greater impacts solely in terms of the stratospheric ozone depletion indicator, which was attributable to substantial nitric acid consumption during silicon wafer recycling. Furthermore, decentralization had greater impacts on the terrestrial ecotoxicity indicator due to nitric acid consumption in silicon wafer recycling and copper sulfate usage in copper recycling. Nitric acid consumption was markedly lower in Centralization than in decentralization. Decentralization consumed approximately 206 kg of nitric acid, whereas Scenario 3 required only 7 kg, representing a significant reduction. Moreover, the recovery yield of the precious materials in Scenario 3 was greater than the recovery yield of the precious materials in decentralization. Landfills had greater impacts across all other impact categories, particularly in terms of human carcinogenic toxicity and mineral resource scarcity, which was driven primarily by the environmental burdens associated with the treatment of used cables. The contribution of each scenario is visualized in Figure 7. Notably, the results highlight the transportation stage as a critical hotspot, significantly contributing to all impact categories for centralization.

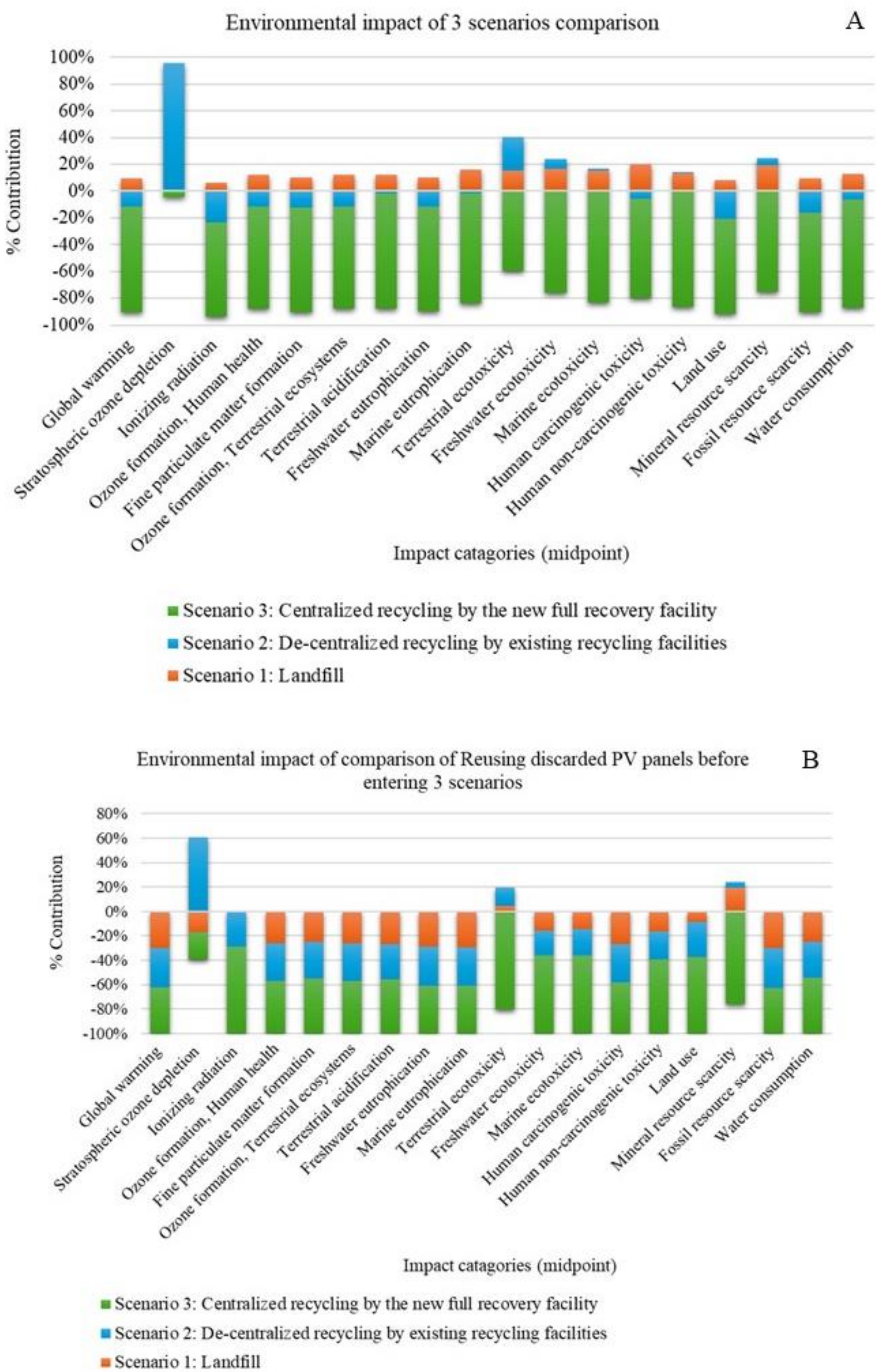

Figure 6 A: Contribution analysis of life cycle impacts (LCIs) associated with 3 discarded PV panel management practice comparisons (midpoints) and B: Contribution analysis of the LCI associated with the comparison of reusing PV panels before entering 3 scenarios (midpoints).

2) LCIA results for the landfill

The results in Figure 7(A) illustrate that the recycling of junction boxes and aluminum frames emerges as the dominant contributor to the environmental impacts associated with landfill. Importantly, this study considers the environmental impact of the landfill disposal stage itself to be negligible. However, the subsequent section delves into the significant opportunity costs associated with the loss of valuable materials within secured landfills. This stage has the most pronounced impacts across all impact categories, with particularly significant contributions to freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, land use, and mineral resource scarcity, each accounting for 100% of the overall impact within secured landfills.

Conversely, the transportation stage contributes to specific impact categories, including ozone formation (31%), fossil resource scarcity (23%), global warming (19%), terrestrial ecotoxicity (15%), terrestrial acidification (11%), fine particulate matter formation (10%), stratospheric ozone depletion (9%), ionizing radiation (3%), human noncarcinogenic toxicity (1%), and water consumption (1%).

Impact contribution analysis further reveals that the recycling stage of junction boxes and aluminum frames constitutes a critical hotspot, significantly contributing to more than 69% of the overall environmental impacts associated with landfill. This substantial contribution can be attributed to the environmental burdens associated with aluminum recycling processes and the treatment of used cables.

- Opportunity loss of valuable materials in secured landfills

Impact contribution analysis further reveals that the recycling stage of junction boxes and aluminum frames constitutes a critical hotspot, significantly contributing to more than 69% of the overall environmental impacts associated with landfill. This substantial contribution can be attributed to the environmental burdens associated with aluminum recycling processes and the treatment of used cables.

Although the environmental assessment of landfill has neglected the disposal stage, the analysis revealed critical oversight: the opportunity cost of losing valuable materials. The recovery of silicon has significantly greater impacts across various environmental categories, including water consumption (85%), ionizing radiation (77%), land use (66%), global warming (62%), fossil resource depletion (62%), stratospheric ozone depletion (55%), fine particulate matter formation (52%), marine eutrophication (47%), human carcinogenic toxicity (45%), ozone formation (40%), and terrestrial acidification (38%). Similarly, the recovery of silver has substantial impacts on mineral resource scarcity (83%), marine ecotoxicity (65%), human noncarcinogenic toxicity (59%), freshwater ecotoxicity (58%), and freshwater eutrophication (41%).

Consequently, the recovery of silicon and silver has emerged as a critical hotspot contributing significantly to the opportunity costs associated with the opportunity loss of valuable materials in secured landfills.

The loss of valuable materials to secured landfills is a significant opportunity cost, which is regrettable considering the potential benefits of recycling.

3) LCIA results for decentralization

As depicted in Figure 7(C), the results reveal that the precious metal recycling stage has the most significant influence, particularly on stratospheric ozone depletion (99%). Within the context of the junction box and aluminum frame recycling, this stage emerges as the primary contributor to the environmental impacts associated with decentralization, which has a substantial influence across a wide range of impact categories.

Like Landfill, the transportation stage within decentralization contributes to environmental burdens across various impact categories, including ozone formation, fossil resource depletion, global warming, terrestrial ecotoxicity, terrestrial acidification, fine particulate matter formation, stratospheric ozone depletion, ionizing radiation, human noncarcinogenic toxicity, and water consumption.

Furthermore, the analysis of impact contributions underscores that the precious metal recycling stage generates environmental credits due to the recovery of valuable metals during the recycling process.

4) LCIA results for centralization

The results in Figure 7(D) show that the transportation stage contributes to environmental burdens across several impact categories, specifically ozone formation (5%), terrestrial ecotoxicity (4%), fossil resource depletion (3%), global warming (2%), stratospheric ozone depletion (2%), fine particulate matter formation (1%), and terrestrial acidification (1%).

Notably, the precious metal recycling stage generates environmental credits due to the recovery of valuable metals during the recycling process. Consequently, the transportation stage emerges as the critical hotspot within Centralization.

The LCA results clearly demonstrate that centralization represents the most environmentally sustainable option for managing discarded c-Si PV panels in Thailand. Although transportation-related emissions have a significant effect in this scenario, overall environmental performance remains superior to that of alternative strategies.

To mitigate transportation-related impacts, currently the primary environmental burden in Central China, developing proximity-based reverse logistics networks is recommended. Strategically establishing takeback centers or transfer stations in regions with high densities of discarded PV panels could reduce transportation emissions by an estimated 15–30%, thereby increasing the net environmental benefits of centralization.

In contrast, decentralization was associated with greater environmental burdens, primarily due to the precious metal recovery phase. This stage was identified as a significant contributor to stratospheric ozone depletion, which is consistent with the findings of the researcher who identified plastic waste disposal as a key factor in elevated ozone depletion impacts during c-Si PV panel recycling (Singh et al., 2023). The contributing plastic components include junction boxes, ethylene-vinyl acetate (EVA) encapsulants, and backsheets. Additionally, the use of strong acids in leaching processes intensifies environmental risks by promoting acidification and eutrophication (Konyratbekova et al., 2015a; b).

To address these concerns, alternative chemical leaching methods have been investigated. For example, replacing nitric acid (HNO_3) with iodine-iodide leaching systems has shown potential in laboratory-scale studies to reduce acidification and eutrophication effects by 25–40% (Chung et al., 2021), offering a more environmentally sustainable approach for precious metal recovery. However, trade-offs between ecosystem quality and resource efficiency have also been reported, emphasizing the need for further optimization.

Recent advancements have explored the combination of low-concentration sulfuric acid leaching with ultrasonication to increase silver recovery from c-Si PV panels. The study demonstrated that this method effectively dissolves silver contacts without the need for secondary precipitation or electrodeposition steps (Click et al., 2024). However, despite its technical efficiency, the process still relies on chemical treatments and thermal preprocessing, such as burning off EVA encapsulants, which may pose environmental challenges if not properly managed.

The research highlighted that many existing delamination techniques lack long-term environmental sustainability (Maani et al., 2020). In response, thermal separation innovations have gained traction. In particular, the heated blade technique, which operates at approximately 300 ^{o}C, has been promoted by the National Science and Technology Development Agency (NSTDA, 2022) as a promising solution for the efficient separation of glass and EVA layers, one of the most challenging steps in PV panel recycling. These innovations play a key role in ongoing research and development efforts focused on improving the efficiency and environmental sustainability of domestic PV recycling operations.

The effectiveness of any PV panel recycling strategy depends heavily on the development of a well-designed reverse logistics system. Establishing collection centers or recycling facilities in areas with high volumes of discarded PV panels can substantially improve operational efficiency. As emphasized by the studies recently, spatial analysis of regional waste flows is essential for determining optimal facility locations and designing robust waste collection systems (Islam and Huda, 2018, Mahmoudi et al., 2019a). These considerations are critical for transitioning to a more sustainable viable EOL framework.

Comparative LCA evidence, as presented in Table S2, supports the prioritization of centralized, high-efficiency recycling systems. For example, the study identified energy consumption and chemical usage as key environmental hotspots in resource recovery from discarded panels (Ansanelli et al., 2021), whereas another study emphasized the role of decentralization in reducing transport emissions (Ardente et al., 2019). Moreover, the research confirmed that landfill is the least sustainable option, underscoring the environmental necessity of recycling alternatives (Faircloth et al., 2019).

5) Enhancing environmental credits through the reusing PV panel

This section evaluates the environmental benefits of incorporating a reuse phase for discarded PV panels in agricultural applications prior to EOL treatment. The LCIA results for all three scenarios were compared with and without this reuse strategy. The reuse phase assumes 85% functional efficiency for an additional five years in agricultural settings, such as water pumping systems. The system boundary is defined as gate-to-grave, including this interim reuse.

The LCIA results, visualized in Fig. 6(B), show that reusing a PV panel before EOL processing significantly enhances environmental performance across most impact categories. Environmental credits were achieved at nearly all the ReCiPe 2016 midpoint and endpoint indicators, with a few exceptions depending on the scenario. These credits are attributed primarily to avoided emissions from conventional electricity generation during the reuse phase and deferred material disposal. The detailed results are presented in Tables S30–S39 in the supplementary material, which present comparative LCIA outcomes for each scenario, with and without the reuse of a PV panel, across both midpoint and endpoint indicators.

- Scenario comparison and results

1) LCIA results for landfill with reused PV panels

Landfills with reused PV panels yield substantial environmental credits across nearly all impact categories, as shown in Figure S2, except for terrestrial ecotoxicity, with an improvement of 578%, and mineral resource scarcity, with a marginal credit of 1%.

Without the reuse of the PV panel, the Landfill method results in burdens across all categories.

Notably, improvements from the reuse of PV panels include the following:

- Global warming: 691%
- Freshwater eutrophication: 1277%
- Marine eutrophication: 1083%
- Fossil resource scarcity: 1053%
- Water consumption: 825%

These results underscore the significant environmental cost of landfill and the benefits of incorporating the reuse of PV panels beforehand.

2) LCIA results of decentralization with the reuse of a PV panel

As shown in Figure S3, reusing a PV panel before decentralization leads to notable environmental improvements, although some categories still result in net burdens due to limitations in Thailand’s current small-scale facilities, including stratospheric ozone depletion (-24%) and terrestrial ecotoxicity (-158%).

Decentralization currently uses highly polluting processes (e.g., nitric acid leaching), contributing to these impacts. Nevertheless, reusing a PV panel offsets significant emissions in other categories:

- Global warming: 490%
- Marine eutrophication: 663%
- Freshwater eutrophication: 626%
- Fossil resource scarcity: 617%
- Human toxicity (noncarcinogenic): 277%

3) LCIA results of centralization with reused PV panels

Centralization with the reused PV panel results in the most balanced and beneficial environmental profile, as presented in Figure S4. Environmental credits are observed across all categories, indicating that this is the most sustainable scenario. Noteworthy improvements included the following:

- Stratospheric ozone depletion: 528%
- Fossil resource scarcity: 530%
- Global warming: 457%
- Human carcinogenic toxicity: 258%

A sensitivity analysis revealed that the transportation distance between solar farms and agricultural reuse sites in the range of 40–100 km only affects the overall impact by 0–1%, which suggests minimal influence from reverse logistics.

- Implementation of the reused PV panel

LCIA results underscore the substantial environmental benefits of integrating the reuse of PV panels prior to EOL treatments. Across all the evaluated scenarios, this reuse phase contributes environmental credits in most impact categories, primarily due to the extension of the product lifespan and the avoidance of emissions from conventional electricity generation. Notably, the strategy of reusing PV panels prior to centralization achieves the lowest overall environmental burden, outperforming both the landfill and decentralization strategies.

The significant environmental reductions observed in categories such as global warming (457%), fossil resource scarcity (530%), and stratospheric ozone depletion (528%) are driven primarily by the complete avoidance of upstream production processes. Unlike recycling, which requires energy-intensive operations such as thermal treatment and chemical separation, the use of a PV panel bypasses the entire “cradle-to-gate” manufacturing phase, including raw material extraction, wafer cutting, cell fabrication, and module assembly. This upstream avoidance also explains improvements in categories related to toxic substance emissions, such as human carcinogenic toxicity (258%) and freshwater ecotoxicity (62%), by eliminating the use of hazardous chemicals typically found in production and recycling. Similarly, reductions in marine eutrophication (386%) and acidification (192%) reflect the avoided emissions of nitrogen and sulfur compounds. Interestingly, while the use of PV panels significantly reduces fossil resource consumption, the near-zero improvement in mineral resource scarcity suggests that energy savings outweigh the environmental benefits more than the recovery of critical minerals does, which represents only a minor share of the overall impact footprint.

The practical application of this strategy is exemplified by the SOLMATE Project in Belgium, which repurposes decommissioned PV panels for agrivoltaic systems and other low-cost decentralized energy solutions in low-income communities (SOLMATE, 2025). This initiative aligns with the European Union's Waste Framework Directive, which emphasizes reuse before recycling and demonstrates the viability of second-life PV panels in agricultural settings (PV magazine, 2025).

Additionally, a study evaluated the integration of reused PV panels within an agrivoltaic system designed for sustainable horticultural production (Nieto-Morone etla., 2025). The results indicate that reused PV panels exhibit strong and consistent energy performance, achieving correlations between irradiance and energy output comparable to those of new panels. Despite slightly lower performance ratios, reused PV panels maintained stable efficiency and operational viability, emphasizing their potential for sustainable applications. This study highlights the environmental and economic advantages of incorporating reused PV panels into agrivoltaic systems, including reductions in raw material extraction, electronic waste generation, and overall environmental impact.

Furthermore, a study investigated the technical reuse potential of c-Si PV panels initially designed for recycling (Schnatmann et al., 2024). This study revealed that, with appropriate quality control and testing, many of these panels are suitable for second-life applications, including agriculture. This approach supports the circular economy by extending the useful life of PV panels and reducing the demand for new raw materials.

- Limitation of reusing a PV Panel

In the context of Thailand and similar developing economies, agricultural reuse offers a promising interim use phase, particularly in rural electrification, greenhouse operations, and water pumping. Such applications require a lower power output and allow for extended utilization of panels beyond their initial warranty period. Therefore, the reuse of PV panels represents an effective means of enhancing environmental sustainability. Nevertheless, several limitations must be considered.

Technically, the reuse of PV panels requires reliable field diagnostics and IEC-standard safety checks to prevent hotspots and safety risks. Additional processes require labor, testing and certification costs, which can erode economic attractiveness compared with new panels or direct recycling.

From a regulatory and institutional perspective, Thailand currently lacks a comprehensive discarded PV panel management framework, and recent policy moves have attracted increasing regulatory attention but have also created uncertainty for second-life markets and cross-border flows.

Lifecycle trade-offs are nuanced; extending service life via reuse can substantially improve the material circularity of PV systems by postponing raw material extraction and reducing waste, but the net climate and resource benefits depend on the efficiency loss of PV panels per year and logistics emissions for collection. All these challenges should be further studied for sustainable solutions.

In conclusion, reusing PV panels prior to centralization is not only the most environmentally favorable option among the evaluated scenarios but also consistent with international findings advocating for circular resource flows. Future research should focus on developing regulatory frameworks, technical standards, and economic incentives to facilitate large-scale implementation of reuse strategies and enhance the overall sustainability of PV panel lifecycle management.

6) Cost-effectiveness (CE) analysis

As presented in Table 2, Centralization presented the highest CE, with the lowest CE value of 5.16E-04. This was followed by decentralization at 6.32E-01 and landfill at 1.38E+00. These values were calculated on the basis of the material yield in USD, which was used as the effectiveness metric.

Silver prices, a key component of the recovered material value, fluctuate daily due to global market dynamics and currency exchange rate variations. In 2024, silver prices in Thailand ranged from approximately 715 to 1,075 USD per kg (Exchange-Rates.org, 2024), whereas the lowest recorded price in 2023 was approximately 640 USD per kg (Exchange-Rates.org, 2023), these minimum and maximum values were used to estimate the potential material value recovered in Scenarios 2 and 3 for cost-effectiveness calculations. The prices of the precious materials used in this study were obtained from the Department of Primary Industries and Mines (2023), as presented in Table S40.

In a subsequent analysis using environmental impact (Pt) as the effectiveness indicator, centralization again emerged as the most cost-effective, with a CE value of −16.25, indicating a high environmental benefit relative to its cost, as illustrated in Table 2. Decentralization and Landfill, with CE values of −0.07 and 0.08, respectively. The negative Pt scores observed in both decentralization and centralization represent environmental credits gained from recycling precious materials from discarded PV panels, thereby offsetting the need for virgin material extraction and processing.

7) Cost-offsetting on cost-effectiveness from reusing a PV panel

An additional cost-offsetting strategy was used to evaluate the reuse of PV panels before the system entered the 3 scenarios. Under these conditions, 1,000 kg of PV panels operating at 70% efficiency could power two water pumps used on a 5-rai (8,000 m^2) farm. With 15 minutes of daily pump operation, the reused panels generate approximately 4,050 kWh per year, resulting in an estimated electricity cost savings of 2,400 USD over five years. This significantly offsets the subsequent recycling costs, particularly for centralization.

In contrast, when a 2% annual inflation rate is applied over a 15-year period, the total cost of implementing Centralization with a newly established full-recovery centralized recycling facility increases to 17.55 USD per 1,000 kg. Despite this, the environmental impact remains favorable at −211.93 Pt, resulting in a CE of –0.08 USD per Pt. Although this reflects robust environmental performance, it is notably less cost-effective than the FRELP system evaluated by the researcher (Faircloth et al., 2019).

- Integrating reuse and recycling strategies

From an economic standpoint, the combined strategy of reusing PV panels prior to centralization has emerged as the most cost-effective EOL solution. This approach not only extends the panel lifespan but also delays resource-intensive recycling processes, thereby reducing operating costs while delivering environmental credits. However, despite these advantages, further research is necessary to increase the accuracy and reliability of economic assessments. In particular, detailed data on logistics costs and capital expenditures are essential for strengthening implementation strategies.

Table 2 Cost-effectiveness analysis per 1,000 kg of discarded PV panels for each practice

Management practices	Total cost (USD)	Recovered material value (USD)	Cost-effectiveness
Based on recovered material value (USD)			
Landfill	404.84	293.85	1.38E+00
Decentralization	358.74	(Min) 552.24	6.50E-01
		567.89	6.32E-01
		(Max) 652.00	5.50E-01
Centralization	13.04	(Min) 25,247.66	5.17E-04
		25,281.68	5.16E-04
		(Max) 25,464.54	5.12E-04

Based on environmental impact (Pt)

Management practices	Total cost (USD)	Environmental impact (Pt)	Cost-effectiveness (Pt per UDS)
Landfill	404.84	34.43	0.08
Decentralization	358.74	−26.45	−0.07
Centralization	13.04	−211.93	−16.25

- Alternative recycling process

Spatial analysis of discarded PV panel generation patterns has been identified as a critical tool for designing cost-efficient collection and recycling networks (Mahmoudi et al., 2019b; Islam and Huda, 2018). Nevertheless, economic barriers to large-scale implementation persist, particularly owing to the high cost of reagents used in chemical leaching processes. Studies from 2015 highlighted these financial limitations as key obstacles to commercialization (Konyratbekova et al., 2015a; b). In response, several technological alternatives have been proposed. For example, iodine–iodide leaching systems have shown promise in reducing acidification and eutrophication impacts. However, this method still faces challenges related to reagent costs and industrial scalability (Konyratbekova et al., 2015a; Chung et al., 2012). Technological advancements are also progressing to address key bottlenecks in material separation. NSTDA has recommended heated blade technology as a promising solution for separating glass from the EVA layer, which is one of the most technically challenging steps in PV panel recycling (Islam and Huda, 2018). Despite these innovations, a study demonstrated the limited economic viability of downstream metal recovery in small-scale recycling systems (Dias et al., 2021). These findings underscore the need for integrated strategies that combine reuse, advanced recycling technologies, and logistics optimization to maximize environmental and economic outcomes.

- Effect of the precious metal recovery price

Another key variable influencing the economic performance of EOL strategies for c-Si PV panels is the market value of silver, one of the primary recoverable materials. Silver prices are inherently volatile and affected by global market dynamics and fluctuations in the THB exchange rate. In 2024, silver prices in Thailand ranged from approximately 715 to 1,075 USD per kg, a notable increase from the 2023 low of 640 USD per kg (Exchange-Rates.org., 2023, 2024). This variability significantly affects the potential revenue from material recovery, particularly in recycling-oriented strategies.

As shown in Table 2, the cost-effectiveness of both decentralization and centralization is highly sensitive to silver price fluctuations. In decentralization, the cost-effectiveness values ranged from 0.65–0.55 depending on the recovered silver value, reflecting moderate improvements over Landfill. In contrast, Centralization demonstrated significantly higher returns, with cost-effectiveness values dropping as low as 5.12E-04, largely due to higher recovery yields and economies of scale. However, these calculations assume optimal recovery conditions and favorable silver prices, underscoring the importance of dynamic market assessments when evaluating recycling feasibility.

Compounding these challenges is the variability in PV panel designs across different generations and evolving manufacturing practices. Notably, reductions in the silver content and silicon wafer thickness directly diminish the material recovery value, thereby lowering the potential revenue from recycling operations. A study emphasized this issue as a significant constraint on economic feasibility (Heath et al., 2022).

Nonetheless, the environmental advantages of silicon wafer recycling remain evident. The study highlighted that recovering silicon offers superior sustainability benefits compared with incineration, due to its scarcity and high reuse potential (Müller et al., 2005). Advancing circularity in PV panel management requires prioritizing redesign strategies that facilitate the deconstruction of panel components, alongside policy incentives that promote high-yield material recovery. These measures align with international circular economy objectives by reducing waste generation and minimizing hazardous material risk (Farrell et al, 2020).

Ongoing research and development efforts aim to improve the cost-effectiveness and scalability of such technologies for domestic application. As silver price volatility continues to affect economic calculations, establishing resilient, adaptable recycling infrastructures will be essential for ensuring the long-term viability of discarded PV panel management systems.

Conclusions

In conclusion, the centralization scenario offers the most environmentally sustainable solution for managing discarded c-Si PV panels in Thailand. Despite the impact from transportation, this approach achieves the lowest overall environmental burdens, particularly when supported by well-planned collection networks. In contrast, decentralization results in greater impacts due to intensive chemical use, especially during precious metal recovery. Emerging techniques such as sulfuric acid leaching with ultrasonication and thermal separation methods such as heated blades offer potential improvements. A focus on efficient recycling technologies and optimized logistics is essential for reducing the environmental footprint of discarded PV panels.

Among the evaluated options, the use of a PV panel prior to centralization offers the greatest environmental benefit. This approach extends the panel lifespan, offsets emissions from conventional electricity generation, and reduces overall environmental impacts. Evidence from projects in Europe, such as the SOLMATE initiative and studies (Nieto-Morone et al. 2025; Schnatmann et al., 2024), confirms the technical and environmental viability of reused panels in agrivoltaic systems. In Thailand and similar contexts, such reuse supports rural electrification and sustainable farming. Promoting this strategy through clear regulations, technical standards, and economic incentives is essential for advancing circular resource use in PV panel management.

Economically, reusing a PV panel prior to centralization offers the most cost-effective EOL solution by extending the panel lifespan and deferring resource-intensive recycling. However, economic viability remains sensitive to fluctuating silver prices, reagent costs, and evolving panel designs that reduce recoverable material value. Optimizing logistics and adopting advanced separation technologies, such as heated blades, can help offset these challenges. Strengthening economic feasibility will require further research, supportive policy frameworks, and scalable technologies to ensure sustainable and resilient PV waste management systems.

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Data availability statement

Information and data used in the study will be disclosed upon request.

Author contributions

Patima Chaichana: Conceptulization, Methodology, Formal analysis, Investigation, Data curation, Writing – Original draft

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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