Supplementary Material (SM)

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

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Table S1 The LCA has been applied in studies related to discarded c-Si PV panels

Goal and scope definition	Life cycle inventory (LCI)	LCIA	Interpretation	Reference
Goal: - Compare the environmental impacts (burden and credit) of the recovery line and the glass reuse line - Determine critical points Scope: - Gate to gate exclude production, use and maintenance Functional unit: - 24 tons of discarded c-Si PV panels (treatment) **Note**: Recover valuable resources and glass	Database: - EcoInvent v.3.5 Input: - Energy and material flows Output: - Products, emissions, waste flows	Software: - SimaPro v.9.0.0.48 (Pre-Consultants) Method: - ReCiPe2016/midpoint (H) V1.1 Environmental impact categories: - Global warming - Fine particulate matter formation - Ozone formation - Terrestrial acidification - Freshwater eutrophication - Marine eutrophication - Human carcinogenic toxicity - Mineral resource scarcity - Fossil resource scarcity - Water consumption	Results: - Comprehensive picture of environmental sustainability of each alternative - Hotspots: energy consumption and chemicals use - Necessity of whole process in the same factory due to transportation issue	Ansanelli et al. (2021)
Goal: - Compare the environmental impacts of two leaching processes (with neutralization) Scope: - Leaching process with 1 M HNO_3/Iodine mixed solution Functional unit: - 1 kg of discarded c-Si PV panels **Note**: Leaching precious metals (recovering Ag and Al)	Database: - Ecoinvent v. 3	Software: - Open-source software, OpenLCA v. 1.10.2 Method: - Eco-indicator 99/endpoint Eco-indicator 95 Environmental impact categories: - Acidification - Eutrophication - Ecotoxicity - Land occupation - Carcinogenic - Climate change - Ionizing radiation - Ozone layer depletion - Respiratory effects - Fossil fuels - Mineral extraction	Results: - Iodine-iodide system: better for ecosystem quality and human health - HNO_3 system: better for resources category	Chung et al. (2021)
Goal: - Compare between experimental recovery vs. landfilling (glass, Al, Si, Ag, Cu) Scope: - EoL (excluded collection) Functional unit: - 5 W c-Si PV panels **Note**: Organic solvent-thermal-chemical treatment (lab scale)	Database: - Ecoinvent v. 3.2	Software: - OpenLCA Method: - ReCiPe/endpoint Environmental impact categories: - Human health - Ecosystems - Resource depletion	Results: - Be profitable from recycling of Al frame and junction box - Not be profitable from downstream metal recovery process	Dias et al. (2021)

Table S1 The LCA has been applied in studies related to discarded c-Si PV panels *(Continued)*

Goal and scope definition	Life cycle inventory (LCI)	LCIA	Interpretation	Reference
Goal: - compare six different delamination methods Scope: - Production to EoL (excluded collection) Functional unit: - 1 square meter of discarded c-Si PV panels **Note**: Thermal, mechanical, and chemical delamination, (literature-based)	Database: - Ecoinvent v. 3.3	Software: - GaBi v. 8.1 Method: - TRACI/midpoint Environmental impact categories: - Smog air - Resources, fossil fuels - Ozone depletion - Human toxicity, c - Human toxicity, n - Human health particulate air - GWP - Eutrophication - Ecotoxicity - Acidification	Results: - Current available recycling technologies might not be eco-friendly nor sustainable for environment (such as chemical treatment)	Maani et al. (2020)
Goal: - Provide minimum environmental impact of solar home systems (SHS) Scope: - Cradle to grave (construction (CO), operation (OP) and end of life (EoL) Functional unit: - 1 MWh of electricity provided to the load **Note**: solar home systems design	Database: - Ecoinvent v. 3.4	Software: - OpenLCA v. 1.9 Method: - ReCiPe/endpoint 2017 Environmental impact categories: - Global warming potential - Resources depletion, - Acidification - Eutrophication potential	Results: - Rising energy tariffs and sales marginal impact on reducing the SHS's environmental impact - Sensitivity analysis applied in this study	Rossi et al. (2020)
Goal: - Compare between central vs. decentralization of recycling facility Scope: - EoL (included collection) Functional unit: - 1000 kg of discarded c-Si PV panels **Note**: Full Recovery End-of-Life Photovoltaic (FRELP) process (pilot scale)	Database: - Ecoinvent v. 2.0	Software: - SimaPro v. 8.5 Method: - ILCD/midpoint Environmental impact categories: - Climate change - Ozone depletion - Human toxicity, cancer effects - Human toxicity, noncancer effects - Human toxicity (ReCiPe) - Particulate matter - Ionizing radiation HH - Photochemical ozone formation - Acidification - Acidification (EDIP) - Terrestrial eutrophication - Freshwater eutrophication - Marine eutrophication - Freshwater ecotoxicity - Mineral depletion - Cumulative energy demand, nonrenewable	Results: - To reduce weight and impact of discarded PV panels, glass, frame, and cables separation must take place at a decentralized facility near the collection location	Ardente et al. (2019)

Table S1 The LCA has been applied in studies related to discarded c-Si PV panels *(Continued)*

Goal and scope definition	Life cycle inventory (LCI)	LCIA	Interpretation	Reference
Goal: - Compare three different pathways: FRELP, LGRF (laminated glass recycling facility), and landfill Scope: - EoL stage Functional unit: - 1000 kg of discarded c-Si PV panels **Note**: discarded c-Si PV panels management in Thailand	Database: - Ecoinvent v. 3.3	Software: - SimaPro v. 8 Method: - ReCiPe/midpoint Environmental impact categories: - Climate change - Ozone depletion - Terrestrial acidification - Freshwater eutrophication - Marine eutrophication - Human toxicity - Photochemical oxidant formation - Particulate matter formation - Terrestrial ecotoxicity - Freshwater ecotoxicity - Marine ecotoxicity - Ionizing radiation - Agricultural land occupation - Urban land occupation - Natural land transformation - Water depletion - Metal depletion - Fossil depletion	Results: - Landfill creates the greatest environmental burden, follow by LGRF and FRELP, respectively.	Faircloth et al. (2019)
Goal: - Compare between incineration vs. recycling (Si wafer) Scope: - EoL (excluded collection) Functional unit: - 72 cells (125 mm x 125 mm) of discarded c-Si PV panels **Note**: Deutsche Solar (pilot scale)	Database: - Ecoinvent 2000	Software: - SimaPro Method: - CML Baseline-2000/midpoint Environmental impact categories: - Abiotic depletion - Global warming (GWP100) - Ozone layer depletion (ODP) - Human toxicity - Photochemical oxidation - Acidification - Eutrophication	Results: - Si wafer losses its value in incineration while recycling and reuse can reduce environmental burden due to scarcity of silicon	Müller et al. (2005)

Life cycle inventory analysis

The required life cycle inventory data

This study identified the necessary inventory data, encompassing both inputs (e.g., raw materials, energy, and resources) and outputs (e.g., products, coproducts, emissions, and waste) associated with downstream processes, including reverse logistics and disposal. Table S2 provides an overview of the required inventory data.

Table S2 Required life cycle inventory data

Life cycle stage	**Life cycle inventory data**	Data source		**Reference**
		Primary data	Secondary data	
Transportation stage				
Reverse logistic	Distance for discarded PV panels transportation		√	Department of Industrial Works, Ministry of Industry, (2016), Latunussa et al. (2016) (Calculation)
	Vehicle type and loading capacity		√	
	Waste and pollution generated during transportation		√	Ecoinvent (2020)
Disposal stage				
Waste management of discarded PV panel	*Landfill*		√	Ecoinvent (2020)
	Decentralization		√	Department of Primary Industries and Mines (2023), Ecoinvent (2020)
	Centralization		√	Ecoinvent (2020), Latunussa et al. (2016)
	Reusing PV panel		√	Based on assumption

The life cycle inventory data of each scenario

On the basis of the defined system boundaries for the proposed discarded PV panel management scenarios in Thailand, the necessary life cycle inventory (LCI) data were identified and collected for each scenario. The following section details the specific LCI data requirements for all the scenarios.

1) Landfill

Data for *Landfill* were obtained through a literature review, encompassing all material compositions, resource inputs, and energy consumption. The weights of the aluminum frame, junction box, and cables removed from discarded PV panels were sourced from the Department of Primary Industries and Mines (2023). Background LCI data were sourced primarily from national databases, with supplementary data obtained from the EcoInvent 3 database Ecoinvent (2020). Table S3 provides life cycle inventory data and sources for *Landfill*.

Table S3 Life cycle inventory data and sources for landfill

Life cycle stage	**Process/materials**	**Source of LCI data**
Transportation stage	- Transport, freight, lorry 3.5-7.5 metric ton, EURO3	Ecoinvent (2020)
Recycle process	- Aluminum frame - Junction box and cable	Department of Primary Industries and Mines (2023), Ecoinvent (2020)
Disposal stage	- Photovoltaic cell, single-Si wafer disposal by secured landfills	Ecoinvent (2020)

2) Decentralization

Data for decentralization were obtained through a literature review, encompassing all material compositions, resource inputs, and energy consumption. The weights of all the materials used in the recycling processes of discarded PV panels were sourced from the Department of Primary Industries and Mines. Background LCI data were sourced primarily from national databases, with supplementary data obtained from the EcoInvent 3 database Ecoinvent (2020). Table S4 provides life cycle inventory data and sources for *decentralization*.

Table S4 Life cycle inventory data and sources for decentralization

Life cycle stage	Process/materials	Source of LCI data
Transportation stage	- Transport, freight, lorry 3.5-7.5 metric ton, EURO3	Ecoinvent (2020)
Recycle process	- Aluminum frame - Junction box and cable - Photovoltaic cell, single-Si wafer - Na_2CO_3 - H_2SO_4 - $CuSO_4$ - HNO_3 - HCl - NaOH - Sugar - Silicon - Silver - Copper - Lead - Solar glass - Polyvinyl Chloride - Electricity	Department of Primary Industries and Mines (2023), Ecoinvent (2020)
Disposal stage	- Solid waste disposal by secured landfills after recycling process - Wastewater treatment	Ecoinvent (2020)

3) Centralization

Data for centralization were obtained through a literature review, encompassing all material compositions, resource inputs, and energy consumption. The weights of all the materials used in the recycling processes of discarded PV panels were sourced from the literature reviews (Faircloth et al., 2019; Latunussa et al., 2016). Background LCI data were sourced primarily from national databases, with supplementary data obtained from the EcoInvent 3 database Ecoinvent (2020). Table S5 provides life cycle inventory data and sources for centralization.

Table S5 Life cycle inventory data and sources for centralization

Life cycle stage	Process/materials	Source of LCI data
Transportation stage	- Transport, freight, lorry 3.5-7.5 metric ton, EURO3 - Transport, freight, lorry 7.5-16 metric ton, EURO3	Ecoinvent (2020)
Recycle process	- Aluminum frame - Junction box and cable - Photovoltaic cell, single-Si wafer - HNO_3 - Ca(OH)2 - Water - Silicon - Silver - Copper - Lead - Solar glass	Ecoinvent (2020), Faircloth et al. (2019), Latunussa et al. (2016),
	- Electricity - Diesel fuel	Ecoinvent (2020), Faircloth et al. (2019), Latunussa et al. (2016),
Disposal stage	- Solid waste disposal by secured landfills after recycling process - Wastewater treatment - NOx emission	Ecoinvent (2020)

LCIA

Following the LCI analysis, the results quantified the consumption of raw materials, resources, chemical substances and energy, as well as the generation of precious metals, waste, and environmental pollutants across all scenarios throughout their life cycles. To assess the potential environmental impacts and elucidate the system–impact relationships, the ReCiPe 2016 midpoint (H) and endpoint (H) methodologies were employed for the LCIA. All available midpoint and endpoint impact indicators were considered for this study, resulting in the evaluation of 18 midpoint and 3 endpoint impact categories. An overview of the midpoint categories and related impact categories is shown in Table S6 (Huijbregts et al., 2017).

Table S6 Overview of the midpoint categories and related impact indicators

Impact category	Indicator	Unit	CF_m	Abbr.	Unit
Climate change	Infrared radiative forcing increase	W x yr/m2	Global warming potential	GWP	kg CO_2 to air
Ozone depletion	Stratospheric ozone decrease	ppt x yr	Ozone depletion potential	ODP	kg CFC-11 to air
Ionizing radiation	Absorbed dose increase	man x Sv	Ionizing radiation potential	IRP	kBq Co60 to air
Fine particulate matter formation	PM2.5 population intake increase	kg	Particulate matter formation potential	PMFP	kg PM2.5 to air
Photochemical oxidant formation: Ecosystem quality	Tropospheric ozone increase (AOT40)	ppb.yr	Photochemical oxidant formation potential: ecosystems	EOFP	kg NO_x to air
Photochemical oxidant formation: Human health	Tropospheric ozone population intake increase (M6M)	kg	Photochemical oxidant formation potential: Humans	HOFP	kg NO_x to air
Terrestrial acidification	Proton increase in natural soils	yr x m^2 x mol/l	Terrestrial acidification potential	TAP	kg SO^2 to air
Freshwater eutrophication	Phosphorus increase in fresh water	yr x m^3	Freshwater eutrophication potential	FEP	kg P to fresh water
Marine eutrophication	Dissolved inorganic nitrogen increase in marine water	yr.kgO_2/kgN	Marine eutrophication potential	MEP	kg N to marine water
Human toxicity: Cancer	Risk increase of cancer disease incidence	-	Human toxicity potential	HTPc	kg 1,4-DCB to urban air
Human toxicity: Noncancer	Risk increase of noncancer disease incidence	-	Human toxicity potential	HTPnc	kg 1,4-DCB to urban air
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	yr x m^2	Terrestrial ecotoxicity potential	TETP	kg 1,4-DCB to industrial soil
Freshwater ecotoxicity	Hazard-weighted increase in fresh waters	yr x m^3	Freshwater ecotoxicity potential	FETP	kg 1,4-DCB to fresh water
Marine ecotoxicity	Hazard-weighted increase in marine waters	yr x m^3	Marine ecotoxicity potential	METP	kg 1,4-DCB to marine water
Land use	Occupation and time-integrated transformation	yr x m^2	Agricultural land occupation potential	LOP	m^2 x yr annual crop land
Water use	Increase of water consumed	m^3	Water consumption potential	WCP	m^3 water consumed
Mineral resource scarcity	Ore grade decrease	kg	Surplus ore potential	SOP	kg Cu
Fossil resource scarcity	Upper heating value	MJ	Fossil fuel potential	FFP	kg oil

From midpoint to endpoint

Endpoint characterization factors (CFe) are directly calculated from their corresponding midpoint characterization factors (CFm) by applying a constant midpoint-to-endpoint factor specific to each impact category as follows.

$CFe_{x,c,a} = CFm_{x,c} \times F_{M \rightarrow E,c,a}$

In this context, 'c' represents the cultural perspective, 'a' designates the area of protection, and 'x' signifies the specific stressor under consideration. The term $F_{M \rightarrow E,c,a}$ denotes the midpoint-to-endpoint conversion factor, which is unique to each cultural perspective ('c') and area of protection ('a'). These midpoint-to-endpoint factors are constant within each impact category, predicated on the assumption that environmental mechanisms operate consistently across all stressors subsequent to the midpoint impact stage along the cause–effect pathway. The results of the endpoint factor analyses are presented in the appendix of this research document.

Interpretation

The interpretation phase of the LCA utilized the results obtained from the inventory and impact assessment stages to critically analyze and interpret the environmental impacts associated with each proposed scenario for discarded PV panel management in Thailand. The calculated environmental impacts accounted for the substitution of virgin materials with recycled or recovered materials obtained from the recycling process. Negative values in our environmental impact assessment indicate a net environmental gain, such as the recovery of valuable resources. This phase culminates in a set of comprehensive conclusions and recommendations derived from the LCA findings. The primary objectives of this interpretation stage are (1) to conduct a comparative assessment of the environmental impacts across the proposed scenarios for discarded PV panel management in Thailand and (2) to identify the environmental hotspots within each scenario.

Life cycle inventory analysis results

The inventory data analysis results for the Landfill

1) Inventory data analysis results of the transportation stage

The transportation data of discarded PV panels in *Landfill* were obtained from secondary data by considering the distance from solar farms to the nearest factory type 106 and then transported to secured landfills. A map of the locations is shown in Figure S1 (Department of Industrial Works, Ministry of Industry, 2014). The average distance from solar farms to the nearest factory type 106 is 50 km. The background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons 100% full load and empty return. The average distance from factory type 106 to secured landfills is 140 km. Similarly, the background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons, 87.25% full load and empty return (Faircloth et al., 2019). All transportation and distribution data for *the landfill* are shown in Table S7.

Table S7 LCI data of the transportation stage for landfill

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (kg)	Return transportation
Transportation of discarded PV panels	Lorry 3.5-7.5 metric ton	Average distance from solar farms to the nearest factory type 106	50.00	1,000.00	0
	Lorry 3.5-7.5 metric ton	Average distance from factories type 106 to secured landfills	140.00	872.50	0

2) Inventory data analysis results of the recycling process

The recycling process of discarded PV panels is manual. Therefore, energy and resources are not used in this recycling process. The quantities of the precious materials for *Landfill* are shown in Table S8.

Table S8 LCI data of the recycling process for landfill

Life cycle stage	Unit	Quantity		Unit	Quantity
Inputs			Outputs		
Aluminum frame	kg	114.00	Aluminum scrap	kg	114.00
Junction box and cable	kg	13.50	PVC (incineration)	kg	12.50
			Copper	kg	1.00

3) Inventory data analysis results of the disposal stage

Disposal stage calculations were conducted on the residual component following the removal of the aluminum frame, junction box, and cable. It was assumed that all generated waste was disposed of in a secure landfill.

Table S9 LCI data of the disposal stage for landfill

Life cycle stage	Unit	Quantity
PV cells	kg	872.50

The inventory data analysis results of decentralization

1) Inventory data analysis results of the transportation stage

The transportation data of discarded PV panels in decentralization were obtained from secondary data by considering the distance from solar farms to the nearest factory type 106 and then transported to the nearest e-waste recycling facilities with capacities greater than 1,000 HP. The waste from recycling processes was further transported to secure landfills. A map of the locations is shown in Figure S1. The average distance from solar farms to the nearest factory type 106 is 50 km. The background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons 100% full load and empty return. The average distance from factory type 106 to the nearest e-waste recycling facility with a capacity greater than 1,000 HP is 316.4 km. Similarly, the background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons, 87.25% full load and empty return (Faircloth et al., 2019). All transportation and distribution data for *decentralization* are shown in Table S10.

Table S10 LCI data of the transportation stage for decentralization

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (kg)	Return transportation
Transportation of discarded PV panels	Lorry 3.5-7.5 metric ton	Average distance from solar farms to the nearest factory type 106	50.00	1,000.00	0
	Lorry 3.5-7.5 metric ton	Average distance from factories type 106 to nearest e-waste recycling facilities (>1000 HP)	316.40	872.50	0
	Lorry 3.5-7.5 metric ton	Average distance from e-waste recycling facilities (>1000 HP) to secured landfills	90.00	17.78	0

2) Inventory data analysis results of the recycling process

The energy and resources used in this recycling process require chemical substances in each stage of the chemical recycling process and electricity consumption in each stage of the thermal recycling process. The quantities of energy and resources used were then calculated per 1,000 kg of discarded PV panels, as shown in Table S11.

Table S11 LCI data of the recycling process for decentralization

Life cycle stage	Unit	Quantity		Unit	Quantity
Inputs			Outputs		
Aluminum frame	kg	114.00	Aluminum scrap	kg	114.00
Junction box and cable	kg	13.50	PVC (incineration)	kg	12.50
PV cells	kg	872.50	Copper	kg	1.00
Na_2CO_3	kg	3.65	Glass	kg	511.50
H_2SO_4	L	215.70	Silicon	kg	18.96
$CuSO_4$	kg	18.25	Silver	kg	0.23
HNO_3	L	142.70	Copper	kg	6.04
HCl	L	0.57	Aluminum hydroxide	kg	20.40
NaOH	L	0.29	Anode slime	kg	0.64
Sugar	kg	0.09			
Electricity	kWh	62.50			

3) Inventory data analysis results of the disposal stage

The disposal stage was calculated by considering wastewater and solid waste generated from the recycling processes. All waste generated was assumed to be secured landfilled.

Table S12 LCI data of the disposal stage for decentralization

Life cycle stage	Unit	Quantity
Dross (wastewater)	kg	17.78
Slag (solid waste)	kg	11.12

The inventory data analysis results of centralization

1) Inventory data analysis results of the transportation stage

The transportation data of discarded PV panels in Central China were obtained from secondary data by considering the distance from solar farms to collection points and then transported to the full recovery factory for discarded PV panels. The locations are based on the literature review (Faircloth et al., 2019). The average distance from solar farms to collection points is 100 km. The background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons 100% full load and empty return. The average distance from collection points to the full recovery factory for discarded PV panels is 150 km. Similarly, the background data of transportation were based on the vehicle type of truck with a loading capacity of 7.5–16 tons 100% full load and empty return (Faircloth et al., 2019). All transportation and distribution data for centralization are shown in Table S13.

Table S13 LCI data of the transportation stage for centralization

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (kg)	Return transportation
Transportation of discarded PV panels	Lorry 3.5-7.5 metric ton	Average distance from solar farms to collection points	100.00	1,000.00	0
	Lorry 7.5-16 metric ton	Average distance from collection points to full recovery factory	150.00	1,000.00	0
	Lorry 3.5-7.5 metric ton	Average distance from full recovery factory to secured landfills	40.00	52.00	0

2) Inventory data analysis results of the recycling process

The energy and resources used in this recycling process require chemical substances, diesel fuel and electricity consumption. The quantities of energy and resources used were then calculated per 1,000 kg of discarded PV panels, as shown in Table S14.

Table S14 LCI data of the recycling process for centralization

Life cycle stage	Unit	Quantity		Unit	Quantity
Inputs			Outputs		
PV panels	kg	1,000.00	Aluminum scrap	kg	183.00
Calcium hydroxide	kg	36.50	Glass	kg	686.00
Nitric acid	kg	7.00	Copper	kg	4.40
Water	kg	310.00	Silicon	kg	35.00
Diesel Fuel	L	1.10	Silver	kg	0.50
Electricity	kWh	114.00			

3) Inventory data analysis results of the disposal stage

The disposal stage was calculated by considering the solid waste generated from the recycling processes. All waste generated was assumed to be secured landfilled.

Table S15 LCI data of the disposal stage for centralization

Life cycle stage	Unit	Quantity
Hazardous waste (solid waste)	kg	52.00

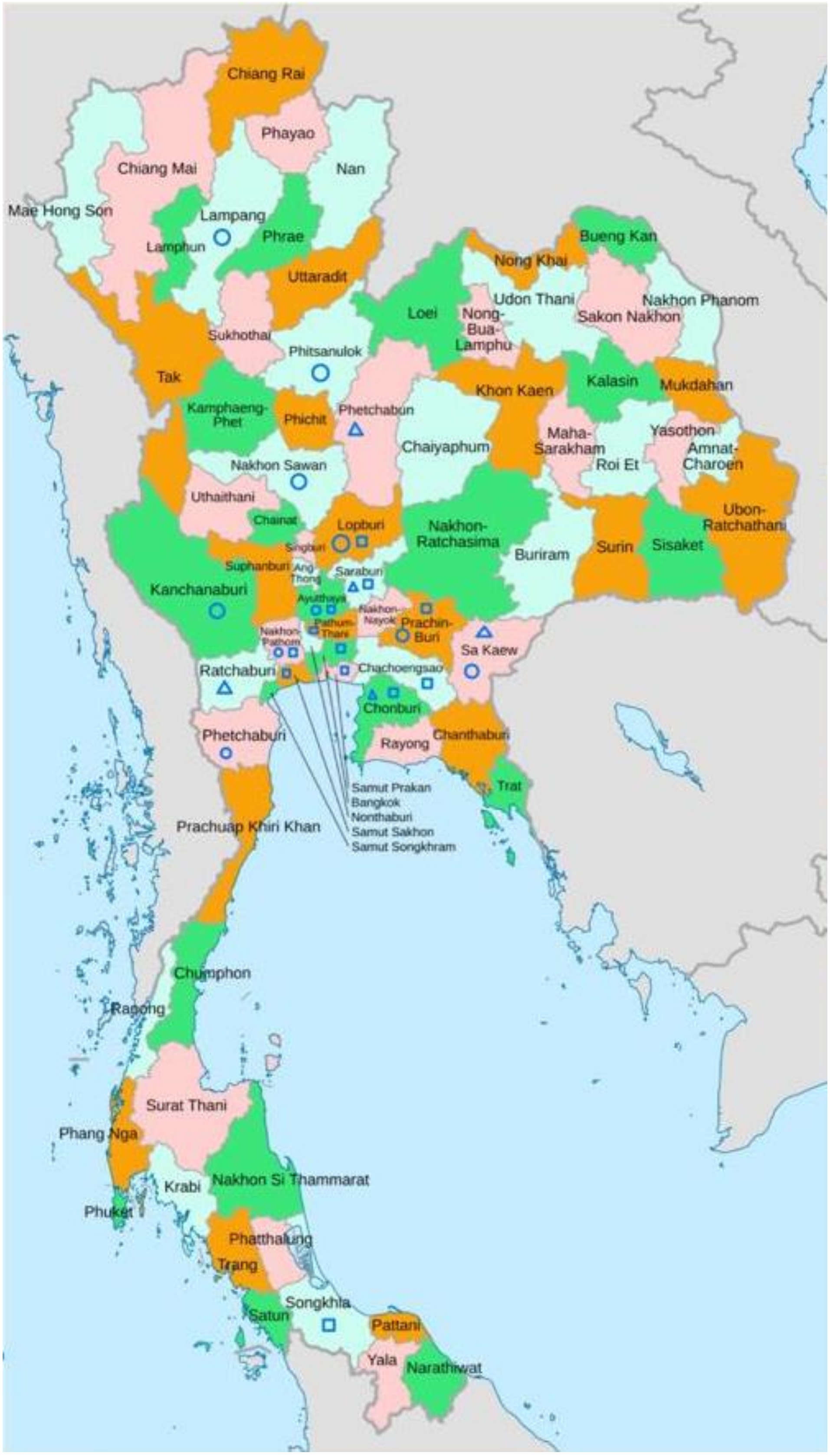

Figure S1 Thailand Map (○ = solar farms, Δ = secured landfills, ☐ = existing recycling facilities).

Reusing a PV panel before entering the other 3 scenarios

1) Life cycle inventory data of each scenario

On the basis of the defined system boundaries for the proposed discarded PV panel management scenarios in Thailand, the necessary LCI data were identified and collected for each scenario.

Data for reusing a PV panel before it enters the other 3 scenarios were obtained through a literature review, which included all material compositions, resource inputs, and energy consumption. The use stage was based on assumptions developed from a literature review. Background LCI data were sourced primarily from national databases, with supplementary data obtained from the EcoInvent 3 database (Ecoinvent, 2020). Table S16 provides a comprehensive list of all inventory data sources.

Table S16 Life cycle inventory data and sources for reusing a PV panel before entering the other 3 scenarios

Life cycle stage	Process/materials	Source of LCI data
Transportation stage	- Transport, freight, lorry 3.5-7.5 metric ton, EURO3	EcoInvent database 3
Use stage	Generating electricity	EcoInvent database 3, based on assumption

2) System boundary of the LCA

The system boundary was the EOL stage or the "gate to grave". The details of each step differ according to the scenario. The overall process of the proposed scenario in *the reuse PV panel* before is visualized in Figure 2(B), and the process of each scenario is described in Figures 5–7.

The scenarios are divided into 2 mainstream methods.

In the second group, *the PV panels are reused* before the other 3 scenarios are entered:

2.1) Landfill

After decommissioning and dismantling, discarded PV panels are transported from solar farms to the agricultural area, which has signed a contract to utilize secondhand PV panels for 5 years. After 5 years, these PV panels were transported back to solar farms and 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.

2.2) Decentralization

After decommissioning and dismantling, discarded PV panels are transported from solar farms to the agricultural area, which has signed a contract to utilize secondhand PV panels for 5 years. After 5 years, these PV panels were transported back to solar farms and 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.

2.3) Centralization

After decommissioning and dismantling, discarded PV panels are transported from solar farms to the agricultural area, which has signed a contract to utilize secondhand PV panels for 5 years. After 5 years, these PV panels were transported back to solar farms and transported from solar farms to 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.

3) Life cycle inventory analysis result

3.1) Inventory data analysis results of the transportation stage

The transportation data of discarded PV panels before they enter the other 3 scenarios were obtained from secondary data by considering the distance from solar farms to the agricultural area that signed a contract to utilize secondhand PV panels for 5 years and then transported them back to solar farms. A map of the locations is shown in Figure S1. The average distance from a solar farm to an agricultural area that has signed a contract to utilize secondhand PV panels for 5 years is 40 km. The background data of transportation were based on the vehicle type of truck with a loading capacity of 3.5–7.5 tons 100% full load and empty return. All transportation and distribution data are shown in Table S17.

Table S17 LCI data of the transportation stage for the reused PV panel before entering the other 3 scenarios

Life cycle stage	Vehicle	Route	Distance (km)	Loading capacity (kg)	Return transportation
Transportation of discarded PV panels	Lorry 3.5-7.5 metric ton	Average distance from solar farms to agricultural area	20.00	1,000.00	0
	Lorry 3.5-7.5 metric ton	Average distance from agricultural area to solar farms	20.00	1,000.00	0

3.2) Inventory data analysis results of the use stage

The use phase analysis considered an agricultural area of 5 rai (8,000 m^2) that necessitates electricity generation for solar-powered water pumps. All the data pertaining to the use stage are presented in Table S18. The following criteria and details were examined:

Table S18 LCI data of the use stage for reusing a PV panel before entering the other 3 scenarios

Life cycle stage	Unit	Quantity
Electricity low voltage	kWh	20,250.00

On the basis of these assumptions, these criteria and details are as follows:

- The specifications of the solar-powered water pumps are 2 HP, 380 V
- The power of the pump is 22.50 kW each
- Fourteen PV panels are required for a pump
- The 1,000 kg PV panels are converted to 2 pumps
- The pumps are operated for 15 minutes/day.
  Hence, the pumps generate 337.50 kWh/month, 4,050 kWh/year or 20,250 kWh per 5 years.

Table S19 Datasets used from Ecoinvent 3, USLCI, and ELCD to collect inventory data and environmental impact data

Dataset
Aluminum alloy {GLO} | market for | APOS, U
Aluminum hydroxide {GLO} | market for | APOS, U
Aluminum (waste treatment) {GLO} | recycling of aluminum | APOS, U
Anode slime, silver and ... from primary copper production {GLO} | APOS, U
Cable, unspecified {GLO} | market for | APOS, U
Calcium chloride {RoW} | market for | APOS, U
Copper {GLO} treatment of used cable
Copper {GLO} | market for | APOS, U
Copper sulfate {GLO} | market for | APOS, U
Electronics, for control units {GLO} | market for | APOS, U
Electricity, low voltage {TH}| market for | APOS, U
Electricity, medium voltage {TH}| market for | APOS, U
Diesel {RoW} | market for | APOS, U
Glass cullet, sorted {RoW} unsorted | APOS, U
Hydrochloric acid {RoW} market for | APOS, U
Municipal solid waste {RoW} treatment of sanitary landfill | APOS, U
Nitric acid {RoW}| market for | APOS, U
Silicon, solar grade {GLO} market for | APOS, U
Silver {GLO} market for | APOS, U
Slag, unalloyed electric {RoW} | residual material landfill | APOS, U
Soda ash, dense {GLO} | market for | APOS, U
Sodium hydroxide, in 50% solution state {GLO} | market for | APOS, U
Solar glass, low-iron {GLO} | market for | APOS, U
Sugar, from sugarcane {GLO} | market for | APOS, U
Sulfuric acid {RoW} | market for | APOS, U
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW} | market for | APOS, U
Transport, freight, lorry 7.5-16 metric ton, EURO3 {RoW} | market for | APOS, U
Water, completely softened, from decarbonized water, at user {GLO}| market for | APOS, U
Waste, from silicon wafer production {RoW} | residual material landfill | APOS, U
Waste incineration of plastics (rigid PVC), EU-27 S
Waste water treatment, chemical reduction/oxidation process

Table S20 LCIA results for Landfill (midpoint)

Impact indicators	Junction box and aluminum frame	Landfill	Transportation	Total
Global warming (kg CO_2 eq)	-2.11E+03	0.00E+00	7.03E+01	-2.04E+03
Stratospheric ozone depletion (kg CFC11 eq)	-4.74E-04	0.00E+00	2.08E-05	-4.53E-04
Ionizing radiation (kBq Co60 eq)	-5.31E+01	0.00E+00	6.19E-01	-5.25E+01
Ozone formation, Human health (kg NO_x eq)	-5.12E+00	0.00E+00	4.66E-01	-4.65E+00
Fine particulate matter formation (kg PM2.5 eq)	-4.19E+00	0.00E+00	9.24E-02	-4.10E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-5.14E+00	0.00E+00	4.70E-01	-4.67E+00
Terrestrial acidification (kg SO_2 eq)	-9.04E+00	0.00E+00	2.41E-01	-8.80E+00
Freshwater eutrophication (kg P eq)	-6.73E-01	0.00E+00	6.01E-04	-6.72E-01
Marine eutrophication (kg N eq)	-5.15E-02	0.00E+00	1.29E-04	-5.13E-02
Terrestrial ecotoxicity (kg 1,4-DCB)	-1.26E+03	0.00E+00	6.72E+02	-5.87E+02
Freshwater ecotoxicity (kg 1,4-DCB)	-3.96E+01	0.00E+00	1.41E-01	-3.95E+01
Marine ecotoxicity (kg 1,4-DCB)	-5.61E+01	0.00E+00	4.91E-01	-5.56E+01
Human carcinogenic toxicity (kg 1,4-DCB)	-3.18E+02	0.00E+00	1.27E-01	-3.18E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-6.77E+02	0.00E+00	1.20E+01	-6.65E+02
Land use (m^2a crop eq)	-1.64E+01	0.00E+00	2.71E-02	-1.63E+01
Mineral resource scarcity (kg Cu eq)	-1.91E+01	0.00E+00	5.08E-04	-1.91E+01
Fossil resource scarcity (kg oil eq)	-4.17E+02	0.00E+00	2.34E+01	-3.93E+02
Water consumption (m^3)	-1.24E+01	0.00E+00	1.01E-01	-1.23E+01

Table S21 LCIA results for the Landfill method (endpoint)

Impact indicators	Junction box and aluminum frame	Landfill	Transportation	Total
Human health (DALY)	1.54E-03	0.00E+00	1.27E-04	1.67E-03
Ecosystem (species.yr)	2.00E-06	0.00E+00	3.18E-07	2.32E-06
Resources (USD2013)	2.39E+01	0.00E+00	1.05E+01	3.44E+01

Table S22 LCIA result of decentralization (midpoint)

Impact indicators	Junction box and aluminum frame	Recycling	Transportation	Total
Global warming (kg CO_2 eq)	-2.11E+03	-9.01E+02	1.34E+02	-2.88E+03
Stratospheric ozone depletion (kg CFC11 eq)	-4.74E-04	1.81E-02	3.95E-05	1.77E-02
Ionizing radiation (kBq Co60 eq)	-5.31E+01	-9.19E+01	1.18E+00	-1.44E+02
Ozone formation, Human health (kg NO_x eq)	-5.12E+00	-3.36E+00	8.87E-01	-7.59E+00
Fine particulate matter formation (kg PM2.5 eq)	-4.19E+00	-2.17E+00	1.76E-01	-6.19E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-5.14E+00	-3.40E+00	8.94E-01	-7.65E+00
Terrestrial acidification (kg SO_2 eq)	-9.04E+00	-2.77E+00	4.59E-01	-1.14E+01
Freshwater eutrophication (kg P eq)	-6.73E-01	-6.99E-01	1.14E-03	-1.37E+00
Marine eutrophication (kg N eq)	-5.15E-02	-3.26E-02	2.45E-04	-8.38E-02
Terrestrial ecotoxicity (kg 1,4-DCB)	-1.26E+03	2.13E+03	1.28E+03	2.15E+03
Freshwater ecotoxicity (kg 1,4-DCB)	-3.96E+01	-4.72E+01	2.68E-01	-8.66E+01
Marine ecotoxicity (kg 1,4-DCB)	-5.61E+01	-1.01E+02	9.34E-01	-1.56E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-3.18E+02	-6.11E+01	2.42E-01	-3.79E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-6.77E+02	-1.67E+03	2.29E+01	-2.33E+03
Land use (m^2a crop eq)	-1.64E+01	-2.90E+01	5.16E-02	-4.53E+01
Mineral resource scarcity (kg Cu eq)	-1.91E+01	-1.30E+01	9.68E-04	-3.21E+01
Fossil resource scarcity (kg oil eq)	-4.17E+02	-2.99E+02	4.45E+01	-6.71E+02
Water consumption (m^3)	-1.24E+01	-1.51E+01	1.92E-01	-2.74E+01

Table S23 LCIA result of decentralization (endpoint)

Impact indicators	Junction box and aluminum frame	Recycling	Transportation	Total
Human health (DALY)	1.54E-03	-2.07E-03	2.42E-04	-2.86E-04
Ecosystem (species.yr)	2.00E-06	-4.34E-06	6.06E-07	-1.73E-06
Resources (USD2013)	2.39E+01	-7.04E+01	2.00E+01	-2.65E+01

Table S24 LCIA result of centralization (midpoint)

Impact indicators	Recycling	Transportation	Total
Global warming (kg CO_2 eq)	-3.15E+03	6.72E+01	-3.08E+03
Stratospheric ozone depletion (kg CFC11 eq)	-8.24E-04	2.01E-05	-8.04E-04
Ionizing radiation (kBq Co60 eq)	-2.16E+02	5.93E-01	-2.16E+02
Ozone formation, Human health (kg NO_x eq)	-9.82E+00	4.54E-01	-9.36E+00
Fine particulate matter formation (kg PM2.5 eq)	-7.49E+00	9.06E-02	-7.40E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-1.00E+01	4.58E-01	-9.55E+00
Terrestrial acidification (kg SO_2 eq)	-1.61E+01	2.34E-01	-1.59E+01
Freshwater eutrophication (kg P eq)	-2.54E+00	5.75E-04	-2.54E+00
Marine eutrophication (kg N eq)	-1.44E-01	1.24E-04	-1.44E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	-1.78E+04	7.14E+02	-1.71E+04
Freshwater ecotoxicity (kg 1,4-DCB)	-3.64E+02	1.45E-01	-3.64E+02
Marine ecotoxicity (kg 1,4-DCB)	-5.79E+02	5.15E-01	-5.79E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-1.77E+02	1.25E-01	-1.77E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-1.08E+04	1.24E+01	-1.08E+04
Land use (m^2a crop eq)	-6.96E+01	2.60E-02	-6.96E+01
Mineral resource scarcity (kg Cu eq)	-6.62E+01	4.87E-04	-6.62E+01
Fossil resource scarcity (kg oil eq)	-8.04E+02	2.24E+01	-7.82E+02
Water consumption (m^3)	-6.37E+01	9.66E-02	-6.36E+01

Table S25 LCIA result of centralization (endpoint)

Impact indicators	Recycling	Transportation	Total
Human health (DALY)	-1.08E-02	1.23E-04	-1.06E-02
Ecosystem (species.yr)	1.14E-02	3.07E-07	1.14E-02
Resources (USD2013)	-2.22E+02	1.01E+01	-2.12E+02

Table S26 LCIA results of the 3 scenario comparisons (midpoints)

Impact indicators	Landfill	Decentralization	Centralization
Global warming (kg CO_2 eq)	-2.04E+03	-2.88E+03	-3.08E+03
Stratospheric ozone depletion (kg CFC11 eq)	-4.53E-04	1.77E-02	-8.04E-04
Ionizing radiation (kBq Co60 eq)	-5.25E+01	-1.44E+02	-2.16E+02
Ozone formation, Human health (kg NO_x eq)	-4.65E+00	-7.59E+00	-9.36E+00
Fine particulate matter formation (kg PM2.5 eq)	-4.10E+00	-6.19E+00	-7.40E+00
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-4.67E+00	-7.65E+00	-9.55E+00
Terrestrial acidification (kg SO_2 eq)	-8.80E+00	-1.14E+01	-1.59E+01
Freshwater eutrophication (kg P eq)	-6.72E-01	-1.37E+00	-2.54E+00
Marine eutrophication (kg N eq)	-5.13E-02	-8.38E-02	-1.44E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	-5.87E+02	2.15E+03	-1.71E+04
Freshwater ecotoxicity (kg 1,4-DCB)	-3.95E+01	-8.66E+01	-3.64E+02
Marine ecotoxicity (kg 1,4-DCB)	-5.56E+01	-1.56E+02	-5.79E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-3.18E+02	-3.79E+02	-1.77E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-6.65E+02	-2.33E+03	-1.08E+04
Land use (m^2a crop eq)	-1.63E+01	-4.53E+01	-6.96E+01
Mineral resource scarcity (kg Cu eq)	-1.91E+01	-3.21E+01	-6.62E+01
Fossil resource scarcity (kg oil eq)	-3.93E+02	-6.71E+02	-7.82E+02
Water consumption (m^3)	-1.23E+01	-2.74E+01	-6.36E+01

Table S27 LCIA results of the 3 scenario comparisons (endpoints)

Impact indicators	Landfill	Decentralization	Centralization
Human health (DALY)	1.67E-03	-2.86E-04	-1.06E-02
Ecosystem (species.yr)	2.32E-06	-1.73E-06	1.14E-02
Resources (USD2013)	3.44E+01	-2.65E+01	-2.12E+02

Table S28 LCIA results of opportunity loss of precious materials in secured landfills (midpoint)

Impact indicators	Aluminum	Silicon	Silver	Copper	Glass	Total
Global warming (kg CO_2 eq)	1.80E-03	2.14E-01	2.57E-02	5.72E-03	9.73E-02	3.43E-01
Stratospheric ozone depletion (kg CFC11 eq)	1.48E-04	1.11E-02	4.88E-03	1.58E-03	2.54E-03	2.00E-02
Ionizing radiation (kBq Co60 eq)	1.73E-03	2.98E-01	3.67E-02	2.58E-02	2.79E-02	3.89E-01
Ozone formation, Human health (kg NO_x eq)	2.26E-03	1.68E-01	7.86E-02	1.40E-02	1.59E-01	4.19E-01
Fine particulate matter formation (kg PM2.5 eq)	1.48E-03	1.30E-01	2.64E-02	2.46E-02	7.12E-02	2.53E-01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	2.75E-03	1.97E-01	9.26E-02	1.66E-02	1.85E-01	4.92E-01
Terrestrial acidification (kg SO_2 eq)	2.20E-03	1.30E-01	3.79E-02	4.49E-02	1.30E-01	3.43E-01
Freshwater eutrophication (kg P eq)	2.28E-02	1.17E+00	1.38E+00	7.16E-01	1.05E-01	3.37E+00
Marine eutrophication (kg N eq)	2.82E-04	1.10E-02	4.40E-03	6.20E-03	1.58E-03	2.32E-02
Terrestrial ecotoxicity (kg 1,4-DCB)	1.67E-01	7.91E-01	9.06E-01	1.13E+01	1.14E+00	1.41E+01
Freshwater ecotoxicity (kg 1,4-DCB)	3.06E+00	1.82E+01	1.25E+02	6.83E+01	2.31E+00	2.14E+02
Marine ecotoxicity (kg 1,4-DCB)	4.83E+00	3.03E+01	2.86E+02	1.18E+02	4.22E+00	4.38E+02
Human carcinogenic toxicity (kg 1,4-DCB)	7.91E-01	1.79E+01	1.28E+01	7.20E+00	1.62E+00	3.95E+01
Human noncarcinogenic toxicity (kg 1,4-DCB)	5.13E-01	4.25E+00	3.62E+01	2.08E+01	6.01E-01	6.18E+01
Land use (m^2a crop eq)	6.13E-05	6.19E-03	1.14E-03	6.39E-04	1.40E-03	9.37E-03
Mineral resource scarcity (kg Cu eq)	6.64E-06	2.45E-06	2.95E-04	5.52E-05	6.75E-07	3.53E-04
Fossil resource scarcity (kg oil eq)	3.49E-03	4.45E-01	5.49E-02	1.46E-02	2.03E-01	7.17E-01
Water consumption (m^3)	1.74E-03	1.53E-01	5.72E-03	2.93E-03	1.75E-02	1.79E-01

Table S29 LCIA results of opportunity loss of valuable materials in secured landfills (endpoint)

Impact indicators	Aluminum	Silicon	Silver	Copper	Glass	Total
Human health (DALY)	6.23E-05	4.04E-03	1.97E-03	1.21E-03	1.91E-03	9.20E-03
Ecosystem (species.yr)	8.66E-08	7.53E-06	1.94E-06	1.12E-06	3.93E-06	1.46E-05
Resources (USD2013)	1.06E+00	9.23E+01	2.24E+01	6.27E+00	7.31E+01	1.95E+02

Comparison between the scenarios without and with PV panel reuse before the 3 scenarios are considered

Table S30 LCIA results for Landfill (midpoint)

Impact indicators	Landfill	Reusing PV panel before entering Landfill
Global warming (kg CO_2 eq)	-2.04E+03	-1.61E+04
Stratospheric ozone depletion (kg CFC11 eq)	-4.53E-04	-4.70E-03
Ionizing radiation (kBq Co60 eq)	-5.25E+01	-7.42E+01
Ozone formation, Human health (kg NO_x eq)	-4.65E+00	-2.35E+01
Fine particulate matter formation (kg PM2.5 eq)	-4.10E+00	-1.55E+01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-4.67E+00	-2.39E+01
Terrestrial acidification (kg SO_2 eq)	-8.80E+00	-3.94E+01
Freshwater eutrophication (kg P eq)	-6.72E-01	-9.25E+00
Marine eutrophication (kg N eq)	-5.13E-02	-6.07E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	-5.87E+02	-3.98E+03
Freshwater ecotoxicity (kg 1,4-DCB)	-3.95E+01	-2.66E+02
Marine ecotoxicity (kg 1,4-DCB)	-5.56E+01	-3.69E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-3.18E+02	-7.74E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-6.65E+02	-7.11E+03
Land use (m^2a crop eq)	-1.63E+01	-3.76E+01
Mineral resource scarcity (kg Cu eq)	-1.91E+01	-1.92E+01
Fossil resource scarcity (kg oil eq)	-3.93E+02	-4.53E+03
Water consumption (m^3)	-1.23E+01	-1.14E+02

Table S31 LCIA results for the Landfill method (endpoint)

Impact indicators	Landfill	Reusing PV panel before entering Landfill
Human health (DALY)	1.67E-03	-3.38E+07
Ecosystem (species.yr)	2.32E-06	-7.35E+04
Resources (USD2013)	3.44E+01	-2.15E+03

Table S32 LCIA result of decentralization (midpoint)

Impact indicators	Decentralization	Reusing PV panel before entering decentralization
Global warming (kg CO_2 eq)	-2.88E+03	-1.70E+04
Stratospheric ozone depletion (kg CFC11 eq)	1.77E-02	1.34E-02
Ionizing radiation (kBq Co60 eq)	-1.44E+02	-1.66E+02
Ozone formation, Human health (kg NO_x eq)	-7.59E+00	-2.65E+01
Fine particulate matter formation (kg PM2.5 eq)	-6.19E+00	-1.76E+01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-7.65E+00	-2.69E+01
Terrestrial acidification (kg SO_2 eq)	-1.14E+01	-4.19E+01
Freshwater eutrophication (kg P eq)	-1.37E+00	-9.95E+00
Marine eutrophication (kg N eq)	-8.38E-02	-6.40E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	2.15E+03	-1.25E+03
Freshwater ecotoxicity (kg 1,4-DCB)	-8.66E+01	-3.13E+02
Marine ecotoxicity (kg 1,4-DCB)	-1.56E+02	-4.69E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-3.79E+02	-8.35E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-2.33E+03	-8.77E+03
Land use (m^2a crop eq)	-4.53E+01	-6.66E+01
Mineral resource scarcity (kg Cu eq)	-3.21E+01	-3.22E+01
Fossil resource scarcity (kg oil eq)	-6.71E+02	-4.81E+03
Water consumption (m^3)	-2.74E+01	-1.29E+02

Table S33 LCIA result of decentralization (endpoint)

Impact indicators	Decentralization	Reusing PV panel before entering decentralization
Human health (DALY)	-2.86E-04	-3.38E+07
Ecosystem (species.yr)	-1.73E-06	-7.35E+04
Resources (USD2013)	-2.65E+01	-2.21E+03

Table S34 LCIA results of centralization (midpoint)

Impact indicators	Centralization	Reusing PV panel before entering centralization
Global warming (kg CO_2 eq)	-3.08E+03	-1.72E+04
Stratospheric ozone depletion (kg CFC11 eq)	-8.04E-04	-5.05E-03
Ionizing radiation (kBq Co60 eq)	-2.16E+02	-2.37E+02
Ozone formation, Human health (kg NO_x eq)	-9.36E+00	-2.82E+01
Fine particulate matter formation (kg PM2.5 eq)	-7.40E+00	-1.89E+01
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-9.55E+00	-2.88E+01
Terrestrial acidification (kg SO_2 eq)	-1.59E+01	-4.65E+01
Freshwater eutrophication (kg P eq)	-2.54E+00	-1.11E+01
Marine eutrophication (kg N eq)	-1.44E-01	-7.00E-01
Terrestrial ecotoxicity (kg 1,4-DCB)	-1.71E+04	-2.04E+04
Freshwater ecotoxicity (kg 1,4-DCB)	-3.64E+02	-5.91E+02
Marine ecotoxicity (kg 1,4-DCB)	-5.79E+02	-8.92E+02
Human carcinogenic toxicity (kg 1,4-DCB)	-1.77E+02	-6.33E+02
Human noncarcinogenic toxicity (kg 1,4-DCB)	-1.08E+04	-1.73E+04
Land use (m^2a crop eq)	-6.96E+01	-9.09E+01
Mineral resource scarcity (kg Cu eq)	-6.62E+01	-6.64E+01
Fossil resource scarcity (kg oil eq)	-7.82E+02	-4.92E+03
Water consumption (m^3)	-6.36E+01	-1.65E+02

Table S35 LCIA result of centralization (endpoint)

Impact indicators	Centralization	Reusing PV panel before entering centralization
Human health (DALY)	-1.06E-02	-3.38E+07
Ecosystem (species.yr)	1.14E-02	-7.35E+04
Resources (USD2013)	-2.12E+02	-2.40E+03

Table S36 LCIA results of the reused PV panel before it enters 3 scenarios (midpoints)

Impact indicators	Landfill	Decentralization	Centralization
Global warming (kg CO_2 eq)	-2.56E+05	-2.57E+05	-2.57E+05
Stratospheric ozone depletion (kg CFC11 eq)	-7.70E-02	-5.89E-02	-7.73E-02
Ionizing radiation (kBq Co60 eq)	-4.45E+02	-5.36E+02	-6.08E+02
Ozone formation, Human health (kg NO_x eq)	-3.46E+02	-3.49E+02	-3.51E+02
Fine particulate matter formation (kg PM2.5 eq)	-2.11E+02	-2.13E+02	-2.14E+02
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-3.53E+02	-3.56E+02	-3.57E+02
Terrestrial acidification (kg SO_2 eq)	-5.60E+02	-5.63E+02	-5.67E+02
Freshwater eutrophication (kg P eq)	-1.55E+02	-1.56E+02	-1.57E+02
Marine eutrophication (kg N eq)	-1.01E+01	-1.01E+01	-1.02E+01
Terrestrial ecotoxicity (kg 1,4-DCB)	-6.44E+04	-6.16E+04	-8.08E+04
Freshwater ecotoxicity (kg 1,4-DCB)	-4.12E+03	-4.17E+03	-4.45E+03
Marine ecotoxicity (kg 1,4-DCB)	-5.70E+03	-5.80E+03	-6.22E+03
Human carcinogenic toxicity (kg 1,4-DCB)	-8.53E+03	-8.59E+03	-8.39E+03
Human noncarcinogenic toxicity (kg 1,4-DCB)	-1.17E+05	-1.18E+05	-1.27E+05
Land use (m^2a crop eq)	-3.99E+02	-4.28E+02	-4.52E+02
Mineral resource scarcity (kg Cu eq)	-2.13E+01	-3.43E+01	-6.84E+01
Fossil resource scarcity (kg oil eq)	-7.50E+04	-7.53E+04	-7.54E+04
Water consumption (m^3)	-1.85E+03	-1.86E+03	-1.90E+03

Table S37 LCIA results of reusing a PV panel before it enters 3 scenarios (endpoints)

Impact indicators	Landfill	Decentralization	Centralization
Human health (DALY)	-6.09E+08	-6.09E+08	-6.09E+08
Ecosystem (species.yr)	2.40E-06	-1.66E-06	1.14E-02
Resources (USD2013)	3.69E+01	-2.40E+01	-2.09E+02

Table S38 LCIA results for 3 scenarios (midpoints)

Impact indicators	Landfill without reusing	Landfill with reusing	Decentralization without reusing	Decentralization with reusing	Centralization without reusing	Centralization with reusing
Global warming (kg CO_2 eq)	-2.04E+03	-2.56E+05	-2.88E+03	-2.57E+05	-3.08E+03	-2.57E+05
Stratospheric ozone depletion (kg CFC11 eq)	-4.53E-04	-7.70E-02	1.77E-02	-5.89E-02	-8.04E-04	-7.73E-02
Ionizing radiation (kBq Co60 eq)	-5.25E+01	-4.45E+02	-1.44E+02	-5.36E+02	-2.16E+02	-6.08E+02
Ozone formation, Human health (kg NO_x eq)	-4.65E+00	-3.46E+02	-7.59E+00	-3.49E+02	-9.36E+00	-3.51E+02
Fine particulate matter formation (kg PM2.5 eq)	-4.10E+00	-2.11E+02	-6.19E+00	-2.13E+02	-7.40E+00	-2.14E+02
Ozone formation, Terrestrial ecosystems (kg NO_x eq)	-4.67E+00	-3.53E+02	-7.65E+00	-3.56E+02	-9.55E+00	-3.57E+02
Terrestrial acidification (kg SO_2 eq)	-8.80E+00	-5.60E+02	-1.14E+01	-5.63E+02	-1.59E+01	-5.67E+02
Freshwater eutrophication (kg P eq)	-6.72E-01	-1.55E+02	-1.37E+00	-1.56E+02	-2.54E+00	-1.57E+02
Marine eutrophication (kg N eq)	-5.13E-02	-1.01E+01	-8.38E-02	-1.01E+01	-1.44E-01	-1.02E+01
Terrestrial ecotoxicity (kg 1,4-DCB)	-5.87E+02	-6.44E+04	2.15E+03	-6.16E+04	-1.71E+04	-8.08E+04
Freshwater ecotoxicity (kg 1,4-DCB)	-3.95E+01	-4.12E+03	-8.66E+01	-4.17E+03	-3.64E+02	-4.45E+03
Marine ecotoxicity (kg 1,4-DCB)	-5.56E+01	-5.70E+03	-1.56E+02	-5.80E+03	-5.79E+02	-6.22E+03
Human carcinogenic toxicity (kg 1,4-DCB)	-3.18E+02	-8.53E+03	-3.79E+02	-8.59E+03	-1.77E+02	-8.39E+03
Human noncarcinogenic toxicity (kg 1,4-DCB)	-6.65E+02	-1.17E+05	-2.33E+03	-1.18E+05	-1.08E+04	-1.27E+05
Land use (m^2a crop eq)	-1.63E+01	-3.99E+02	-4.53E+01	-4.28E+02	-6.96E+01	-4.52E+02
Mineral resource scarcity (kg Cu eq)	-1.91E+01	-2.13E+01	-3.21E+01	-3.43E+01	-6.62E+01	-6.84E+01
Fossil resource scarcity (kg oil eq)	-3.93E+02	-7.50E+04	-6.71E+02	-7.53E+04	-7.82E+02	-7.54E+04
Water consumption (m^3)	-1.23E+01	-1.85E+03	-2.74E+01	-1.86E+03	-6.36E+01	-1.90E+03

Table S39 LCIA results for 3 scenarios (endpoints)

Impact indicators	Landfill without reusing	Landfill with reusing	Decentralization without reusing	Decentralization with reusing	Centralization without reusing	Centralization with reusing
Human health (DALY)	1.67E-03	-6.09E+08	-2.86E-04	-6.09E+08	-1.06E-02	-6.09E+08
Ecosystem (species.yr)	2.32E-06	2.40E-06	-1.73E-06	-1.66E-06	1.14E-02	1.14E-02
Resources (USD2013)	3.44E+01	3.69E+01	-2.65E+01	-2.40E+01	-2.12E+02	-2.09E+02

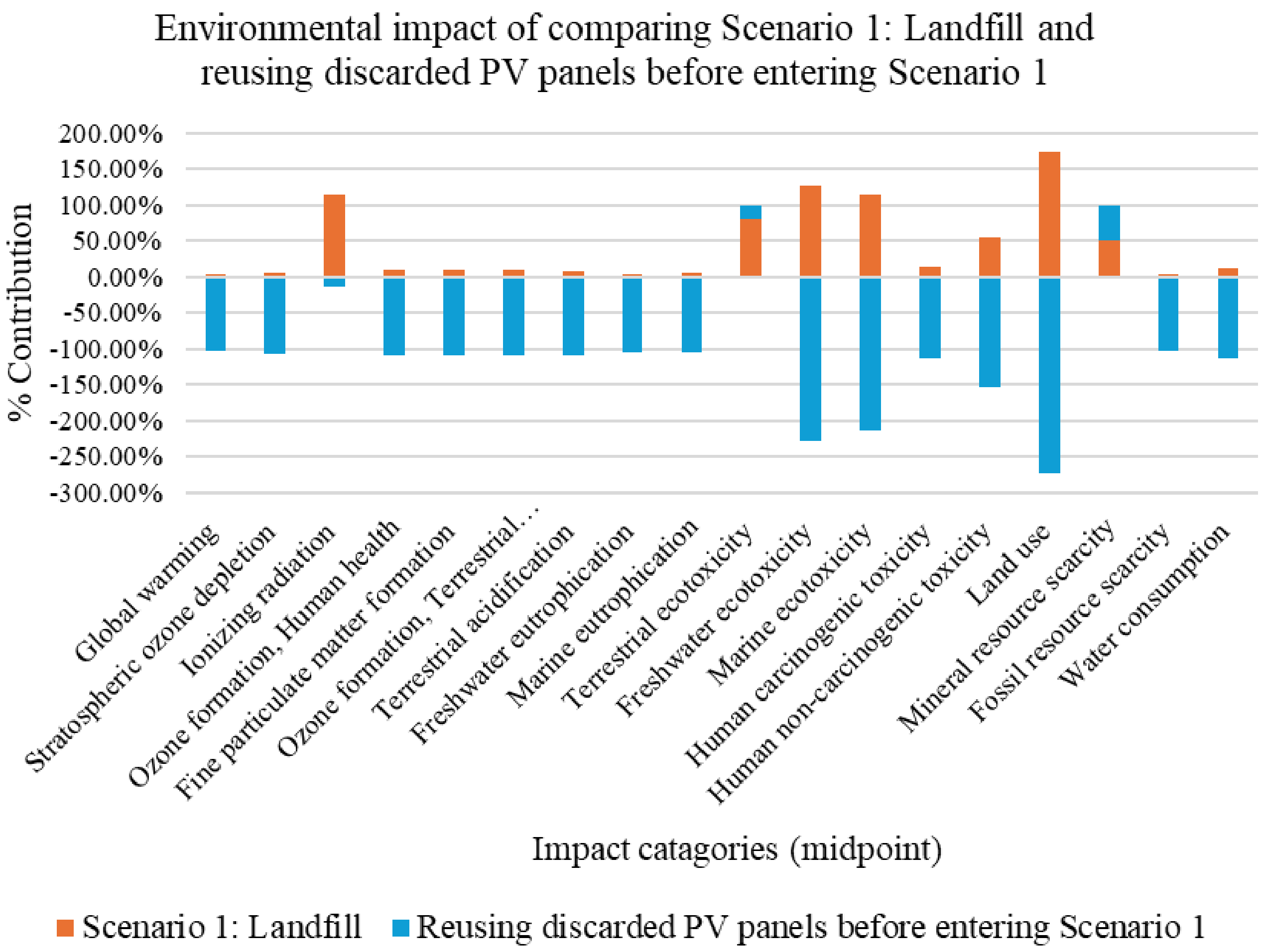

Figure S2 Contribution analysis of the LCI associated with a comparison of the Landfill and Reusing PV panels before landfill (midpoint).

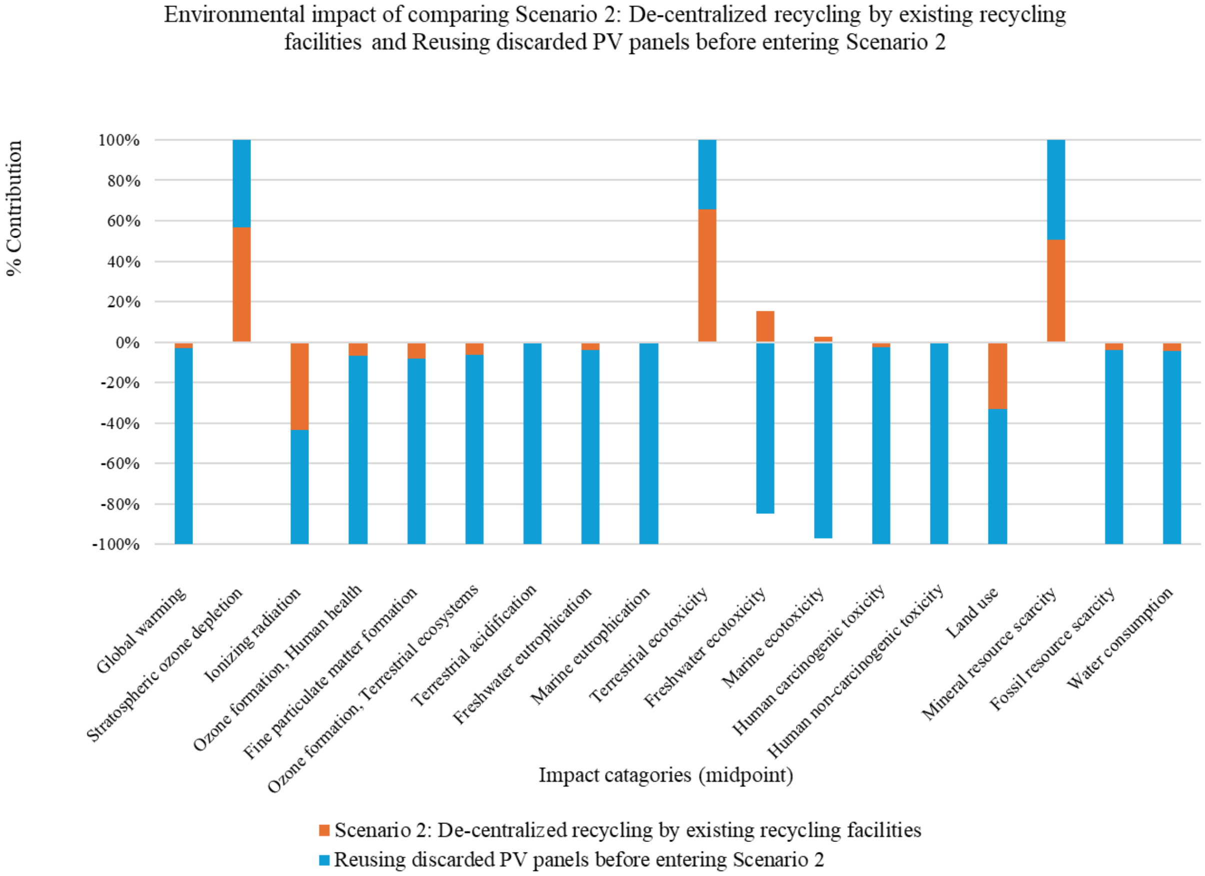

Figure S3 Contribution analysis of the LCI associated with a comparison of decentralization and reusing PV panels before entering decentralization (midpoint).

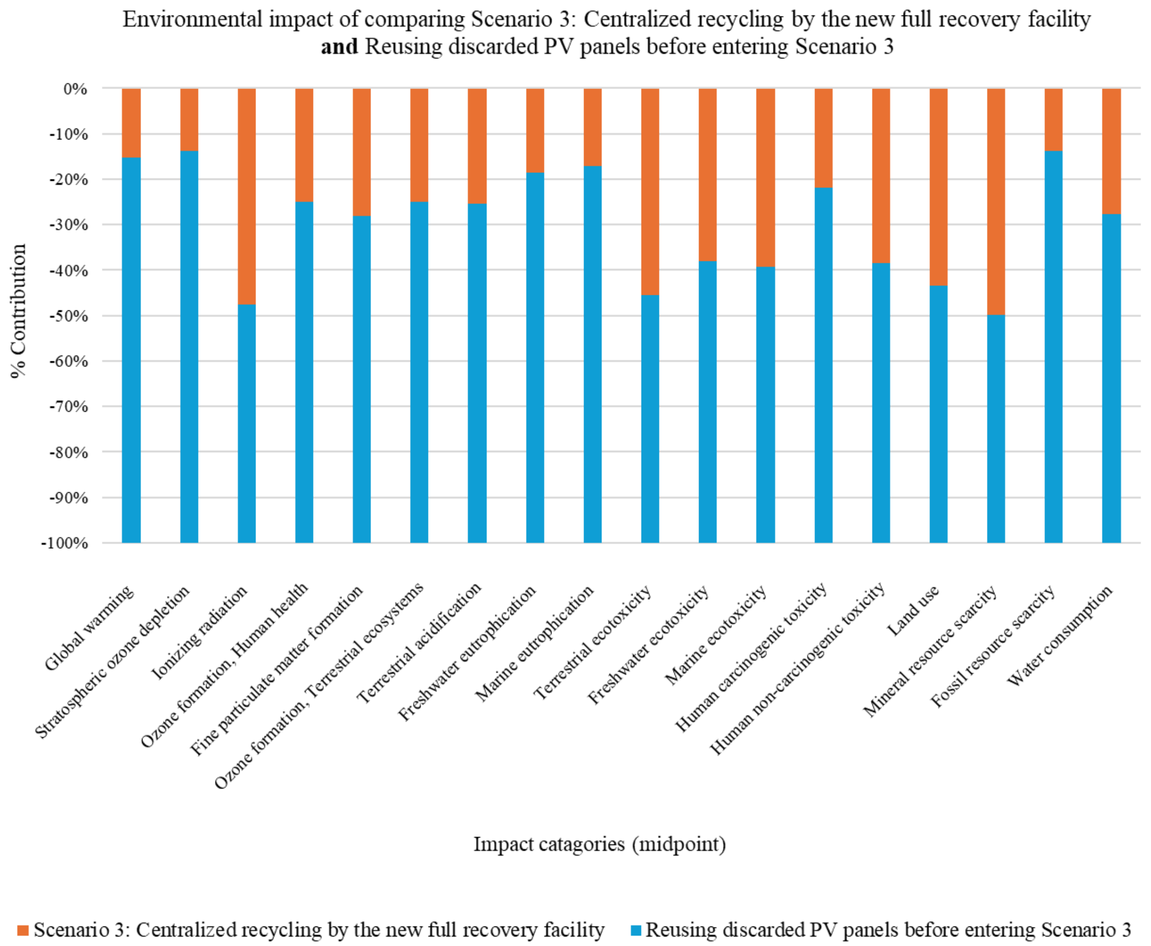

Figure S4 Contribution analysis of LCI associated with a comparison of centralization and reusing PV panels before entering centralization (midpoint).

Table S40 The prices of precious materials are acquired from the Department of Primary Industries and Mines (2023)

Materials	Price (THB/ per kg)
Aluminum	85.00
Junction box and cable	50.00
Glass	1.00
Silicon	84.00
Silver	25000.00
Copper	300.00

Remark: ** The average USD-THB exchange rate in 2024 was 1 USD = 35.273 THB (Exchange-Rates.org, 2025)