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From Waste to Resource: Sustainable Recycling Strategies for Monocrystalline Solar Panels in Indonesia

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Abstract

The rapid growth of photovoltaic (PV) installations in Indonesia, projected to exceed 8.5 GW by 2030, is expected to generate over 1 million tons of solar panel waste by 2050, highlighting the urgent need for end-of-life (EoL) management. This study evaluates the environmental impacts of monocrystalline PV panels and examines suitable recycling strategies for Indonesia. A Life Cycle Assessment (LCA) framework compares landfill and recycling scenarios using Global Warming Potential (GWP) and Cumulative Energy Demand (CED), supported by sensitivity analysis. Results show that aluminum recycling can reduce GWP by up to 83% and CED by 95% compared to primary production. Mechanical recycling and direct reuse are the most feasible options given local market conditions and technological readiness, while advanced recycling requires additional support. Extending panel lifespan and further improving efficiency further reduce emissions and accelerate carbon payback. The study emphasizes the need for a national PV waste management framework that integrates recycling with circular economic strategies. Policy measures such as Extended Producer Responsibility and fiscal incentives, combined with cross-sector collaboration, are crucial to ensuring a sustainable, low-carbon solar energy transition in Indonesia.

1. Introduction

Solar energy has become one of the main pillars of the global energy transition towards a cleaner, more sustainable system [1]. Amidst growing awareness of climate change, the use of renewable energy sources is becoming increasingly important, including in developing countries such as Indonesia [2, 3]. Solar panels, especially monocrystalline types, are increasingly used due to their high efficiency and long service life [4, 5]. Indonesia's energy policy sets a target of 23% for new and renewable energy (NRE) in the national energy mix by 2025. Solar energy is one of the main contributors [6]. By 2023, Indonesia's solar power plant (PLTS) installations had reached a total capacity of more than 400 MW. Most of this is from the commercial and household sectors [7, 8]. Despite its enormous potential, the widespread use of solar panels also raises questions about their overall environmental impact [9]. In the context of sustainability, it is important to assess the environmental impact of solar panels throughout their entire life cycle. This ensures that clean energy solutions do not create new environmental problems in the future [10].

Although solar panels generate electricity without emissions during their operation, production requires large amounts of energy and chemicals. This can result in a significant carbon footprint [11]. A more comprehensive approach is needed to measure sustainability using a Life Cycle Assessment (LCA) [12], which assesses a product's environmental impact from raw material extraction to final disposal [13]. Using LCA, we can identify environmental hotspots in the life cycle of solar panels. We can also evaluate the potential for reducing impacts through recycling or production efficiency options [14, 15]. In Indonesia, LCA studies for solar panels are still very limited. They have not become a reference in sustainable energy policy planning [16]. Therefore, it is important to understand how local contexts, such as material sources, tropical climates, and underdeveloped recycling infrastructure, can affect the results of solar panel LCA analyses [17].

Various global studies have examined LCA analyses of solar panels using different approaches, including methodologies, recycling scenarios, and carbon footprint assessments. According to Portillo et al., photovoltaic (PV) module production accounts for more than 70% of the module's life-cycle emissions [18]. Similarly, Muteri et al. [19] conducted a meta-analysis of more than 20 PV LCA studies and found that monocrystalline technology has the highest carbon footprint among PV technologies. Maalouf examined silicon and aluminum recycling scenarios and concluded that the potential for impact reduction could reach 30%. In addition, Raabe emphasized the importance of considering regional context in LCA assessments, particularly regarding grid energy sources and climate [20]. In Southeast Asia, several studies, such as those by Bosnjakovic, Ajulian, and Lim, show that the tropical climate accelerates the degradation of PV modules, thereby affecting their service life and LCA results [21–23]. Research by Neumuller et al. [24] compares LCAs of rooftop PV and PV farms and concludes that logistics and material efficiency also play important roles. In Indonesia itself, studies are still limited. Fitriana et al. and Siregar et al. are early examples of PV LCA studies, but they have not comprehensively addressed the end-of-life (EoL) and recycling aspects [25, 26].

The rapid global expansion of PV deployment has drawn increased attention to the EoL management of PV modules, especially considering sustainability and circular-economy goals. Recycling crystalline silicon (c-Si) PV modules has become a crucial strategy for reducing environmental impacts while enabling the recovery of valuable materials from solar waste. Numerous studies have examined the technical dimensions of PV module recycling, emphasizing both conventional and emerging methods for material recovery [27]. For example, enzymatic delamination [28] and the use of green solvents such as deep eutectic solvents [29] or hydrothermal recycling techniques [30] represent promising eco-friendly alternatives to traditional mechanical and chemical processes. From a policy and economic perspective, the role of regulatory mechanisms such as deposit-return schemes and subsidies has been evaluated in the Chinese context, suggesting their potential to promote recycling behavior among stakeholders [31, 32]. Insights from the European Union's PV waste management strategies also offer valuable guidance for countries like China in designing effective recycling frameworks [33]. Furthermore, advancing the circular economy requires not only recycling but also exploring the reuse potential of retired PV modules, which poses its own set of challenges and opportunities [34]. Despite progress, gaps remain in optimizing recovery efficiency, reducing processing costs, and integrating recycling systems with broader sustainability goals [35].

Based on the literature reviewed, most LCA studies on solar panels are still dominated by studies in developed countries, with the assumption of clean energy supplies and existing recycling infrastructure. Although several studies in Southeast Asia have emerged, LCA studies in Indonesia remain very limited and have not comprehensively addressed the EoL phase or the potential for recycling local materials. This gap is crucial given Indonesia's tropical climate, its underdeveloped recycling infrastructure, and its reliance on imported PV modules. This study offers novelty by presenting a simple LCA analysis of monocrystalline panels, widely used in Indonesia, and by evaluating the environmental impact of each life-cycle phase. With this approach, the study is expected to make an initial contribution to the formulation of PV waste management policies and encourage the integration of the circular economy into national solar energy development. The main objectives of this study are to identify the largest contributors to the environmental impact of monocrystalline PV panels and explore potential recycling scenarios as long-term environmental improvement solutions.

2. Materials and Methods

2.1 Study Design and Scope

This study applies a cradle-to-grave LCA to evaluate the environmental impacts of monocrystalline PV panels in Indonesia and compare landfill and recycling scenarios at EoL. The analysis covers the entire product life cycle, from raw material extraction through manufacturing, distribution, the use phase (20–25 years), and final disposal or recycling. The system boundary focuses exclusively on PV module components, including glass cover, EVA (Ethylene Vinyl Acetate), silicon cells, and aluminum frames, excluding auxiliary components such as inverters and wiring systems. The assessment is based on projected installed PV capacity from 2015 to 2030 and on waste generation potential from 2035 to 2050.

2.2 Data Collection and Sampling Procedure

Data were collected from multiple verified national and international sources to ensure accuracy and reproducibility.

- Installed capacity data (2015–2030) were obtained from the Electricity Supply Business Plan (RUPTL) [36], National Electricity General Plan (RUKN), and the Ministry of Energy and Mineral Resources (ESDM) annual performance reports [37].
- PV panel specifications were based on standard monocrystalline modules commonly used in commercial and residential installations in Indonesia, with an average panel dimension of 355 mm × 350 mm and a weight of 1,501 kg [38, 39].
- Material composition per panel was derived from Erkata [38], which provides the proportion of glass cover (0.4043 kg), EVA (0.0621 kg), silicon (0.0562 kg), and aluminum frame (0.9788 kg).
- Recycling emission factors and energy demand coefficients for aluminum, silicon, and glass were compiled from published literature and technical reports [20, 27, 40, 41].

2.3. Experimental Setup and Calculation Procedure

The procedure to estimate PV waste volume and environmental impacts was structured in a step-by-step sequence to ensure reproducibility:

- Determining installed PV capacity per year: Annual installed capacity values were compiled from the RUPTL and ESDM datasets and tabulated for the period 2015–2030.
- Estimating PV panel area and weight: Each 1 MWp installation was assumed to occupy 1 hectare (10,000 m²) in tropical regions such as Indonesia [39]. Using the panel size and weight, the total material mass per MWp was calculated using Equation 1.

$$M_p = \frac{M_{p1}}{(L_{p1} \times W_{p1})} \quad (1)$$

where M_p is a panel weight (kg), $M_{p1}$is the initial panel weight (kg), $L_{p1}$is the panel length (m), $W_{p_1}$is the panel width (m).

- Estimating the Amount of PV Panel Waste: Based on Service Life and Annual Capacity: Equation 2: Calculating the annual PV panel weight

$$M_{pt} = M_p \times P_t \quad (2)$$

where M_{pt} is the total annual panel weight (kg), P_t is the annual installed capacity (MW).

- Projecting waste generation timeline: Assuming a 20-year lifespan, the EoL year for each installation batch was determined. For example, the capacity installed in 2015 was projected to become waste in 2035. This calculation was applied cumulatively each year through 2050.
- Material flow estimation: For each waste year, the total volume of glass, EVA, silicon, and aluminum waste was estimated using material composition ratios per panel.
- LCA modeling: Two scenarios were modeled to evaluate the environmental impacts of waste management options. In the landfill scenario, all materials were assumed to be disposed of in a landfill, with no recovery or reuse. In contrast, the recycling scenario assumed a material recovery rate of 60–80%, reflecting the potential for mechanical recycling and direct reuse methods appropriate to local conditions [27, 28, 34].
- Equations used: Global Warming Potential (GWP) was calculated using Equation 3:

$$GWP = m \times GWPf \quad (3)$$

where; GWP is global warming potential (kg CO2-eq), m is material mass (kg), $GWPf$ is emission factor (CO2-eq).
Meanwhile, to calculate Cumulative Energy Demand (CED), use Equation 4:

$$CED = m \times CED \in \quad (4)$$

Where CED is the cumulative energy demand (Mega Joule) or (MJl), m is the material mass (kgl), and $CED \in$ is the energy demand coefficient (Mega Joule/kilogram) or (MJ/kg).

- Tools and software: This study included several specialized applications to support data analysis and visualization. Microsoft Excel 365 was utilized for numerical calculations and material flow modeling. IBM SPSS 29 was employed for regression trend analysis of capacity growth, while Python (Matplotlib) was used to visualize GWP and CED comparisons. Additionally, QGIS 3.28 was applied for geographic information system (GIS) mapping to identify PV installation clusters across Indonesia and validate their spatial distribution.

2.4. Recycling Scenarios and Technological Assessment

To ensure the method reflects real conditions in Indonesia, recycling scenarios were classified into:

- Full recovery / direct reuse: second-life application of lightly damaged panels.
- Mechanical recycling: physical separation of aluminum, glass, and silicon using crusher and separator machines.
- Advanced methods: chemical treatment and laser-assisted delamination were modeled for sensitivity analysis, although not yet widely available in Indonesia [27–30, 34].

2.5. Sensitivity Analysis

Sensitivity analyzes were conducted for two key variables:

- Service life (20, 25, and 30 years) to assess the impact on carbon payback time and total waste accumulation.
- Module efficiency (16%–24%) to evaluate avoided emissions and energy return on investment (EROI).

These analyzes allowed for understanding how operational improvements and technological advancements could influence environmental outcomes [42, 43].

3. Results and Discussion

3.1 Accumulated Installed PV

The projected growth of installed PV in Indonesia from 2015 to 2030 is shown in Table 1, with reference to the 2015-2024 installed capacity from the 2024 ESDM Performance Report [37], while the reference for installed capacity from 2025 to 2030 is from the 2025 PLN RUPTL [36]. As shown, the average growth in installed PLTS capacity is 29%. If this growth trend continues, the number of solar panels reaching the end of their service life (EoL) over the next 20-30 years will also increase significantly. This requires an early solar panel waste management strategy to avoid environmental burdens and maximize the recycling potential of valuable materials from these used panels.

In Figure 1, the cumulative installed capacity of PV solar panels shows an exponential growth trend from 2015 to 2030, with capacity increasing from 33.40 MW to 8,500.59 [MW]. Based on the exponential regression equation y = 16,688e0,4026 and the coefficient of determination R^2 = 0,9556, it can be concluded that this growth is highly significant and well predicted. The sharp increase that began in the mid-2020s indicates that Indonesia will face the potential for large amounts of PV panel waste starting in the 2040s, making EoL management system planning very important to support the sustainability of the energy transition.

In calculating PV panel waste from solar power plants per year, the approach used refers to the Erkata methodology [38], where for PV panel dimensions Width = 355 [mm] x Length = 350 [mm], the weight is 1.501 [kg], using formula 1, the weight per m = 12.08 [kg]. And with the assumption that 1 [MWp] = 1 hectare or 10,000 [m^2] for tropical regions [39] (such as Indonesia), using formula 2, the weight of PV panels per capacity of 1 [MW] = 120,833.80 [kg], as shown in Table 2.

Estimated Amount of PV Panel Waste Based on Service Life and Annual Capacity: PV solar panels generally have a service life of 20 to 30 years, depending on module quality, environmental conditions, and maintenance standards. Assuming a conservative average service life of 20 years, PV panel waste in Indonesia is projected to begin emerging around 2035. This refers to Table 1, which shows that the capacity of solar power plants installed since 2015 is 33.40 MW and is expected to reach the end of its operational life during that period.

According to Table 3, by 2050, Indonesia is projected to generate more than 1 million tons of PV solar panel waste as the panels installed two to three decades earlier reach the end of their service life. If not handled properly and systematically, this amount of waste can cause serious environmental impacts, ranging from hazardous material pollution to increased burden on the national waste management infrastructure. In addition, PV panel waste contains recoverable resources, including aluminum, copper, and glass, that would otherwise be discarded without a circular economy approach. This situation underscores the importance of the Indonesian government's role in preparing a comprehensive EoL management system for PV panels starting now. Given the projected exponential surge in installed PV panel capacity expected in the 2030s, an EOL management strategy needs to be designed early to anticipate the volume of waste that will emerge in the coming decades. This encompasses national policy formulation, advancements in recycling technologies, and the creation of an integrated PV waste management ecosystem oriented toward environmental sustainability.

3.2 Various Recycling Methods

Comparative Analysis of PV Panel Waste Management. Various recycling methods have been developed to recover valuable materials, including glass, aluminum, copper, silver, and silicon. Each method employs a

Table 1. Accumulated installed PV.

Year	Installed Capacity [MW]	
	Total	**New**
2015	33,40	33,40
2016	43,10	9,70
2017	50,90	7,80
2018	67,80	16,90
2019	150,60	82,80
2020	172,90	22,30
2021	207,70	34,80
2022	292,30	84,60
2023	600,00	307,70
2024	800,59	200,59
2025	1,600.59	800.00
2026	2,600.59	1,000.00
2027	4,200.59	1,600.00
2028	5,700.59	1,500.00
2029	6,800.59	1,100.00
2030	8,500.59	1,700.00

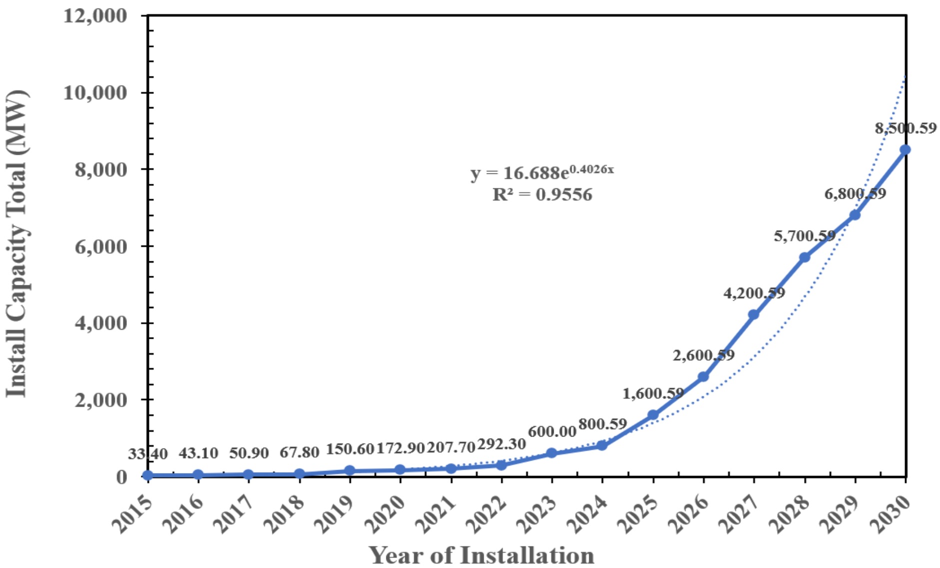

Figure 1. Accumulation of installed PV panels.

Table 2. Estimated Weight of PV Panel Waste Material Based on Capacity per MW.

Type of Waste Material	**Weight of Material per Panel [kg]** (1)	**Coefficient for area m²** (2)	**Material Weight per m² [kg]** (3)=1x2/1000	**Weight/10,000m² [Kg]** (4) = 3x10,000
Glass cover	0.4043	0.12425	3.25	32,539.24
EVA (Ethylene Vinyl Acetate)	0.0621	0.12425	0.50	4,997.99
Silicon (PV)	0.0562	0.12425	0.45	4,523.94
Aluminium Frame	0.9788x	0.12425	7.88	78,772.64
Total	**1.501**		**12.08**	**120,833.80**

distinct technical approach and involves different operational steps, investment levels, and energy requirements, resulting in varying levels of recovery efficiency and economic feasibility. To support the selection of the most suitable recycling strategies for Indonesia, these methods must be regularly evaluated for technological readiness, cost implications, environmental benefits, and market potential. Table 4 provides a comparative overview of these methods, summarizing the technologies employed, the recycling processes involved, the required energy inputs, the investment levels, and their respective advantages, disadvantages, and economic benefits. This structured comparison serves as a decision-support reference for designing an effective and context-appropriate PV panel recycling framework in Indonesia.

Table 3. Estimated amount of PV panel waste based on service life and annual capacity.

Year	Capacity Service life [MW]	Waste Volume [Tons]
2035	33,40	4,035.85
2036	43,10	5,207.94
2037	50,90	6,150.44
2038	67,80	8,192.53
2039	150,60	18,197.57
2040	172,90	20,892.16
2041	207,70	25,097.18
2042	292,30	35,319.72
2043	600,00	72,500.28
2044	800,59	96,738.33
2045	1,600.59	193,405.38
2046	2,600.59	314,239.18
2047	4,200.59	507,573.26
2048	5,700.59	688,823.97
2049	6,800.59	821,741.15
2050	**8,500.59**	**1,027,158.62**

Table 4. Comparative handling of PV waste modules.

Method	Technology Used	Methods Used	Energy Required	Initial Investment	Advantages	Disadvantages	Economic Benefits
Mechanical recycling	Shredder, crusher, magnetic separator, vibrating sieve	Panel destruction, physical separation of glass, aluminum, and cables	Relatively low (only electricity for mechanical machines)	Low-moderate	Fast process, low operating costs	Low silicon quality, only suitable for metallurgy	Obtains used glass & aluminum that can be sold, reducing disposal costs
Thermal treatment	Furnace or rotary kiln	Heating to burn EVA & resin layers	High (around 400-600°C; 1-2 MWh per ton of panels)	Moderate-high	Cleans cells of plastic, increases material value	High energy consumption, potential for gas pollution	Provides clean raw materials for the recycling industry
Chemical treatment	Chemical reactor tank, circulation pump, and filtration	Leaching & etching to extract silver, clean silicon	Moderate (for pumping & temperature control)	Moderate	Extraction of valuable metals such as silver, higher silicon purity	Chemical liquid waste that must be treated	Higher selling value of metal & silicon, significant return from silver sales
Laser-assisted delamination	Laser scanning system, conveyor	Laser separates glass & EVA without damaging cells	Low-moderate (for lasers & motors)	High (advanced technology)	Minimal waste, more precise, more intact cell results	Expensive, technology is still developing	Potential to resell used cells, not just materials
Full recovery / direct reuse	Performance testing equipment, repair tools, laminator	Panel check and repair or replace busbar; junction box sold for second life	Low	Low-medium	Very low carbon footprint, fast process	Only for panels with minor damage	Sold as second-life panels, priced at 30-50% of new panels
Landfill	Transport trucks, bulldozers, landfill site	Panels disposed of in landfill & buried	Low	Low	Simplest, fastest	Damages the environment; loss of material value; potential for heavy metal contamination	Disposal costs are cheaper in the short term, but expensive in the long term (land remediation costs)

Table 5. Analyze each method using SWOT.

Method	Strengths	Weaknesses	Opportunities	Threats
Mechanical recycling	Low operating costs, fast process, simple technology	Low-quality silicon produced	Many end-of-life panels, large recycling market potential	Fluctuating prices for used materials; demand for recycled materials may be low
Thermal treatment	Cleans plastic well, cleaner material results	High energy consumption, potential for gas pollution	Demand for quality recycled materials	Increasingly strict emissions regulations & environmental standards
Chemical treatment	Can extract valuable metals & produce purer silicon	Chemical liquid waste requires treatment, a more complex process	High silver & silicon prices increase value	Rising chemical waste treatment costs, Strict liquid waste regulations
Thermo-chemical process	Obtains high-purity, high-value silicon	High initial investment & process costs; more complicated	Desirable for new cell industries (remanufacture)	Fluctuating polysilicon prices are cheaper than competing technologies
Laser-assisted delamination	Minimal pollution, relatively intact cell results	Expensive & still developing technology	Demand for second-life cells or reused cells	Risk of commercialization failure; high initial reuse cell costs
Full recovery / direct reuse	Low carbon footprint, fast & inexpensive process	Only for lightly damaged panels	The second-life panel market is difficult for developing countries	Limited volume;
Landfill	Simplest & fastest process	Damages the environment; loss of entire material value	Very old, Cheap short-term disposal costs	Expensive remediation costs, government bans, and a poor reputation

Table 6. Feasibility assessment of solar panel recycling methods.

Method	Investment Affordable	Technology Available Locally/Easy to Adopt	Relatively Low Energy	Not Too Complex Process	Local Market Exists (Material / Second Life Panels)	Feasibility Rating
Full recovery / direct reuse	Yes	Yes	Yes	Yes	Yes	1
Mechanical recycling	Yes	Yes	Yes	Yes	Yes	2
Thermal treatment	No	Yes	No	Yes	Yes	3
Chemical treatment	No	No	No	No	Yes	4
Laser-assisted delamination	No	No	Yes	No	Yes	5
Thermo-chemical process	No	No	No	No	Yes	6
Landfill	Yes	Yes	Yes	Yes	No	7

Note: Feasibility rating 1 = most feasible; 7 = least desirable.

Some of the methods discussed will certainly require further evaluation to determine their suitability for PV module waste management in Indonesia. To support strategic decision-making, a structured assessment tool is necessary to examine not only the technical performance of each method but also its economic, regulatory, and market context. The SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides a comprehensive framework for identifying internal factors (technological capabilities and limitations) and external factors (market dynamics, regulatory environment, and economic opportunities) that may influence the adoption of each recycling method. Table 5 presents the SWOT analysis for the various PV recycling technologies, enabling a more informed comparison and prioritization of options that align with Indonesia's current infrastructure, investment capacity, and policy landscape.

To further clarify the assessment results, Table 6 presents the evaluation criteria and feasibility ratings for each recycling method, while Table 7 provides the supporting rationale and contextual factors behind those assessments. These tables explain the logical basis and local considerations that determine why certain methods are easier or more challenging to implement such as capital requirements, technological readiness, energy demand, process complexity, and potential economic value in the local market.

3.2.1 Recycling vs. Landfill Scenario on GWP Effects

Table 8 presents a simulation comparing the landfill scenario (without recycling) and the recycling scenario (60%–80% material recovery) to evaluate the GWP for 1,000 kg of pure materials or waste [40].

The data presented in Table 8 were subsequently visualized in Figure 2 to provide a clearer comparison between the landfill and recycling scenarios.

Table 7. Explanations of method feasibility ratings.

Method	Reasons
Full recovery / direct reuse	Low investment, simple technology (testing + improvement), quick to implement; suitable for reuse in off-grid/rural sectors.
Mechanical recycling	Crusher machines and separators are readily available; electricity costs and investment are relatively affordable; there is a market for the resulting products (glass, aluminum) in Indonesia.
Thermal treatment	Requires high-temperature industrial furnaces; high energy consumption (electricity & gas) is a burden, but the technology is relatively well known (cable recycling industry).
Chemical treatment	Requires chemical control & liquid waste treatment, which is not yet established in many areas; requires skilled chemical personnel; moderate to high costs.
Laser-assisted delamination	Advanced technology, expensive, rarely available; requires specialized human resources and maintenance; only suitable if there is technology transfer and subsidies.
Thermo-chemical process	Combination of thermal and chemical processes; most expensive and complex; difficult to implement without significant research support and foreign investment.
Landfill	Low cost and easy, but not economically viable, and highly contrary to circular economy principles, and prone to strict regulations

Table 8. Simulation of global warming potential (GWP).

Types of Material / Waste Recycling (ex., 1000 [Kg])	Landfill [kg (CO_2-eq) /kg]	Recycling [kg (CO_2-eq) /kg]	Efficiency [%]
Silica Sand (SiO_2) / Glass Cover	4,400	730	-83.0%
Silica Sand (SiO_2) / Silicon (PV)	4,400	3,080	-30.0%
Alumina (Al_2O_3) / Aluminum Frame	11,890	2,010	-83.0%

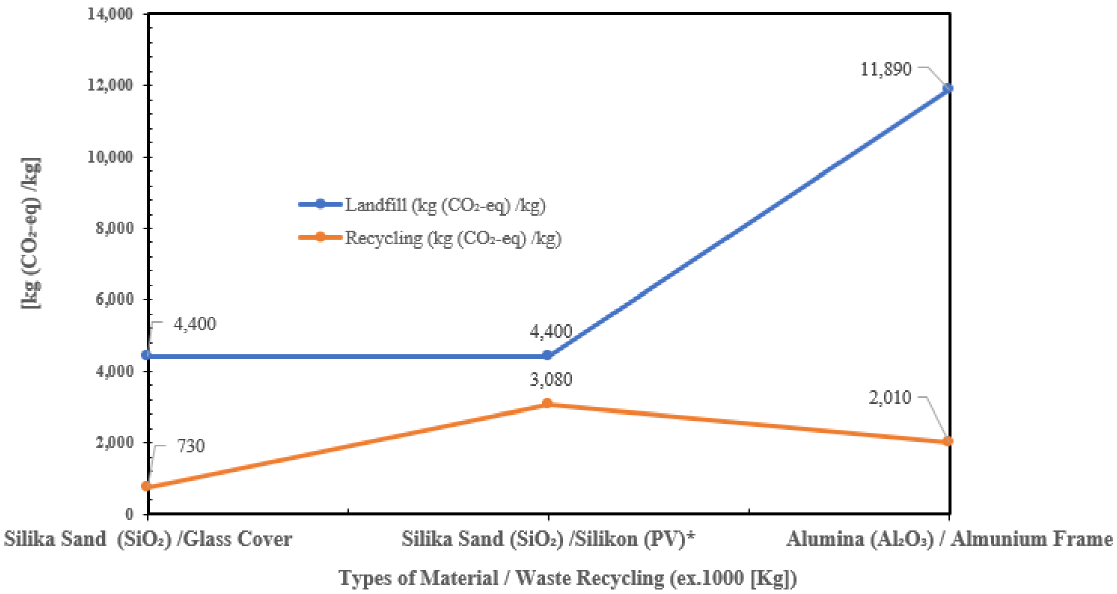

Figure 2. Simulation of global warming potential (GWP).

Figure 2 illustrates the GWP comparison of three main types of materials in solar panels (PV) when managed through two scenarios: landfill disposal and recycling. The vertical axis shows the GWP value in kg CO: -equivalent per 1,000 kg of material, while the horizontal axis shows the type of material analyzed. Silica Sand (SiO:) for Glass Cover shows a striking difference between the landfill option (t4,400 kg CO:-eq) and the recycling option (#730 kg CO:-eq), reflecting a very high emission reduction efficiency. This shows that recycling glass from PV modules significantly reduces GHG emissions. Silica Sand (SiO:) for Silicon (PV) shows a smaller GWP reduction, from around 4,400 kg CO:-ek to 3,080 kg CO:-ek when recycled. This indicates that the silicon recycling process still faces efficiency challenges and has a lower potential for reducing emissions than glass and aluminum. Alumina (AlO3) for Aluminum Frames recorded the highest GWP value in the landfill scenario (+11,890 kg CO_2e), but the recycling process significantly reduced emissions to around 2,010 kg CO_2e. This confirms the importance of recycling aluminum to reduce carbon emissions from the renewable energy sector.

Table 9. Simulation of cumulative energy demand (CED).

Types of Material / Waste Recycling (ex., 1000 Kg)	Landfill Mega Joule (MJ)	Recycling Mega Joule (MJ)	Efficiency (%)
Silica Sand (SiO_2) / Glass Cover	12.000	4.000	-67%
Silica Sand (SiO_2) / Silicon (PV)	300.000	210.000	-30%
Alumina (Al_2O_3) / Aluminum Frame	210.000	10.500	-95%

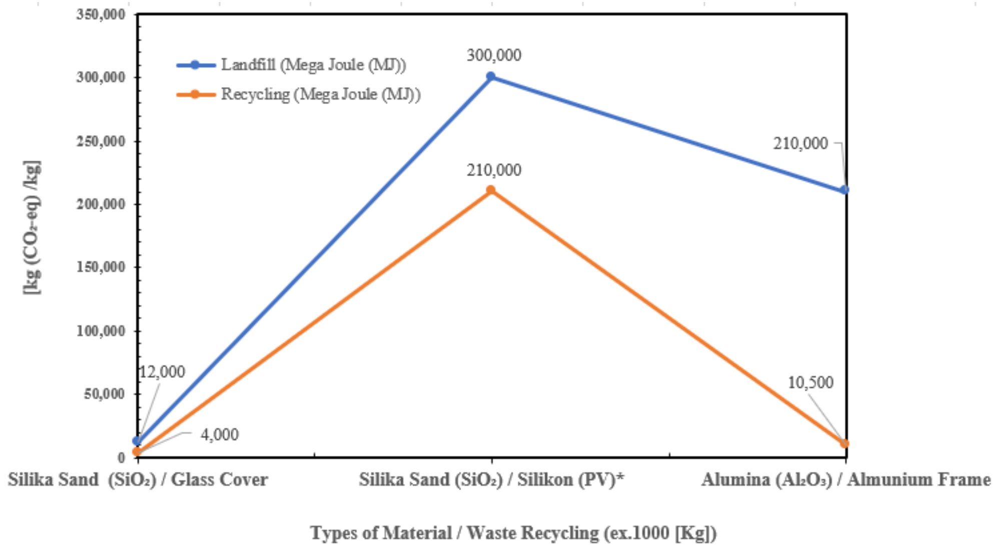

Figure 3. Simulation of cumulative energy demand (CED).

Overall, this graph confirms that a recycling approach, especially for materials such as glass and aluminum, is highly effective in reducing carbon emissions in the life cycle of solar panels. Efforts to improve recycling technology for PV silicon are important to ensure GWP reduction efficiency is evenly distributed across all major components.

3.2.2 Recycling vs. Landfill Scenarios for CED

Table 9 presents a simulation comparing the landfill scenario (without recycling) and the recycling scenario (60%–80% material recovery) to evaluate the CED for 1,000 kg of pure materials or waste [41].

The data presented in Table 9 were subsequently visualized in Figure 3 to illustrate the comparison between landfill and recycling scenarios for the CED of 1,000 kg of pure materials and waste.

3.3 Sensitivity Analysis of Panel Lifespan and Efficiency

The graph in Figure 3 presents a simulation of the CED for three main components of solar panels: protective glass (glass cover), silicon for PV cells, and aluminum frames. A comparison is made for two waste management scenarios: landfill (without recycling), represented by the blue bar, and recycling (with a recycling rate of 60-80%), represented by the red bar, for every 1,000 kg of material. The silicon material shows the highest CED value in the landfill scenario, at around 350,000 MJ, decreasing to around 250,000 MJ when recycled. This shows that silicon production is very energy-intensive, but recycling can significantly reduce the energy burden. However, the CED value of silicon remains high, so improving the efficiency of recycling technology is important to support the sustainability of PV modules.

In aluminum materials, recycling efficiency is even more dramatic. The CED of aluminum in the landfill scenario reaches around 250,000 MJ, but drops sharply to less than 50,000 MJ in the recycling scenario. This shows that aluminum is an ideal material for circular economy strategies because its recycling is much more energy efficient than primary production. In contrast, glass from silica sand (SiO:) shows a much lower CED in both scenarios, below 20,000 MJ. This indicates that although glass recycling remains important, its contribution to reducing total energy consumption is not as significant as that of silicon and aluminum. Thus, decarbonization efforts in the photovoltaic industry should focus on improving recycling systems for silicon and aluminum, the two most significant components of the solar module energy cycle.

3.3.1 Sensitivity Analysis on Service Life

The analysis indicates that extending the service life of PV systems from 20 to 25 years substantially influences the carbon emission intensity per kilowatt-hour (kWh) of

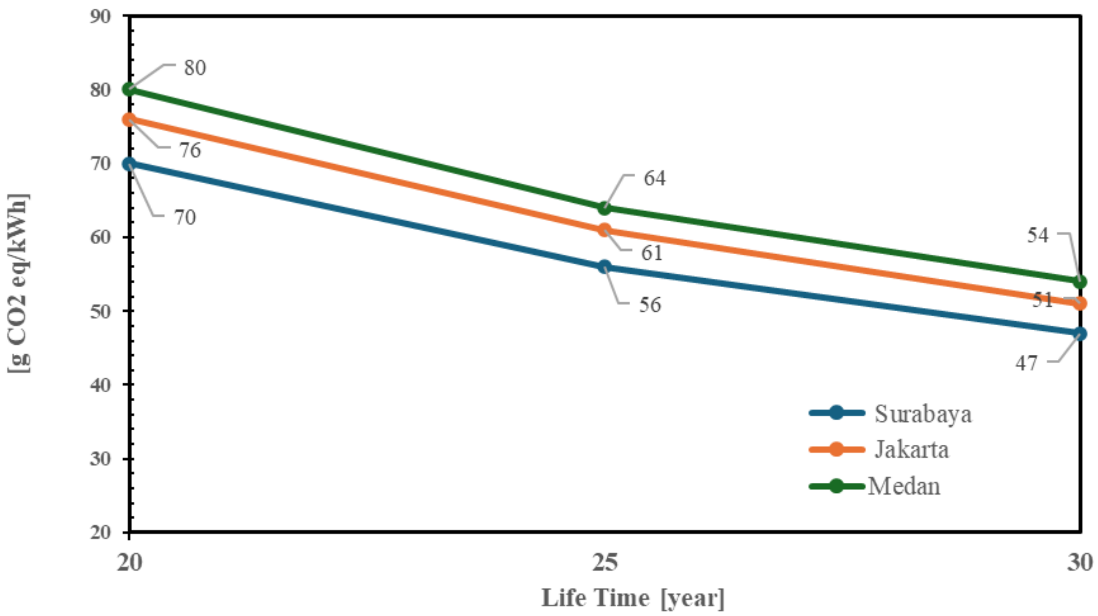

Figure 4. Greenhouse gas emission levels with varying levels of solar radiation over varying lifespans.

Table 10. Analysis of different system lifespans and different solar irradiance for an average system capacity of 2 to 15 kWp [44].

Indicator	Unit	Surabaya (yr)			Jakarta (yr)			Medan (yr)		
		20	25	30	20	25	30	20	25	30
Solar irradiation	kWh/m2 /yr	1,982.2			1,806,8			1,724,1		
GHG Emission	g CO2eq/kWh	70	56	47	76	61	51	80	64	54
PBT	year	7.65	7.65	7.65	7.92	7.92	7.92	8.00	8.00	8.00
ROI	dimensionsionless	3.09	3.42	3.89	2.79	3.25	3.75	2.52	3.10	3.43

electricity produced. The level of greenhouse gas (GHG) emissions, as shown in Figure 4, indicates that extending the system's operational lifespan significantly reduces the emission intensity per unit of electricity generated. Compared to a system lifespan of 20 years, GHG emissions are reduced by approximately 19% when the lifespan is extended to 25 years. The longer the system can operate optimally, the greater its contribution to reducing the cumulative carbon footprint. The findings stress the importance of PV system longevity and sustainability in optimizing environmental and economic gains.

Two key indicators for evaluating the technical performance and economic viability of PV systems are Energy Payback Time (EPBT) and Energy Return on Investment (EROI). Table 10 summarizes the relationship between these indicators and varying levels of solar irradiation, showing how system performance improves under higher solar resource conditions. As solar irradiation increases, electricity generation also increases, thereby reducing the environmental burden per unit of energy and gradually lowering both GHG emission intensity and EPBT. In parallel, EROI values increase, reflecting higher cumulative energy returns over the system's operational lifespan [42]. This pattern highlights that extended operations enhance both environmental and economic performance. Therefore, implementing strategies such as proper maintenance, high-quality components, and effective operational management is essential to maximize the long-term benefits and sustainability of PV systems.

3.3.2 Sensitivity Analysis on Module Efficiency

The analysis results presented in Table 11 clearly demonstrate that increasing the efficiency of PV modules from 18% to 22% has a substantial impact on the system's overall environmental performance. Higher module efficiency increases the annual energy output from 280.8 to 343.2 kWh/m^2/year, representing an approximate 22% gain. This finding is consistent with Fraunhofer ISE (2023), which reported that a 1% increase in crystalline module efficiency is associated with a proportional increase in annual energy generation. As a result, avoided carbon emissions also rose from 196.56 to 240.24 kg CO_2/m^2/year, directly contributing to emission reduction goals. More importantly, this improvement shortens the carbon payback time (CBT) from 2.5 to 1.9 years, indicating a faster return on the environmental investment of PV installations.

Table 11. CBT calculation based on module efficiency.

Module Efficiency (%)	Energy	Output Avoided Emissions [kg CBT CO/m/yr]	Production Emission [kg CO_2/m^2[	CBT
16%	250	175	520	2.97
18%	280.8	196.6	491.4	2.5
20%	312	218.4	475	2.18
22%	343.2	240.2	456.5	1.9
24%	374.4	262.1	440	1.68

These results align with previous research, which emphasizes that lower CBT is a key indicator of PV system effectiveness in mitigating greenhouse gas (GHG) emissions [43]. Furthermore, improving module efficiency optimizes land use and supports material utilization, enhancing the environmental benefit per unit of installed capacity. Therefore, Table 11 underscores the strategic importance of efficiency improvements as a priority action to accelerate net-zero targets and strengthen the sustainability of renewable energy systems.

Based on this study's findings, three critical points warrant further discussion and strategic consideration for Indonesia's solar energy transition. First, the exponential growth in installed PV capacity presents a major waste management challenge for the future. The capacity is projected to exceed 8.5 GW by 2030, meaning the earliest systems installed around 2015 will reach the end of their lifespans by 2035. This corresponds to the typical lifespan of 20–25 years for monocrystalline PV panels [1, 2, 6]. If no structured management system is put in place, this will lead to more than 1 million tons of PV waste by 2050, as observed in other countries with similar deployment scales [31, 32]. This situation mirrors global experiences, in which countries such as China and members of the European Union have had to adopt early regulatory and technological responses, including deposit-return schemes and mandatory recycling directives [31, 33]. Therefore, early policy planning for Indonesia is crucial to prevent future environmental burdens and to support a sustainable energy transition [16, 25, 26].

Second, the environmental performance of recycling scenarios is shown to be significantly better than that of landfilling. LCA results demonstrate that aluminum recycling can reduce GWP by up to 83% and CED by up to 95% compared to primary aluminum production. Similar patterns have been observed globally, where recycling aluminum and glass from PV modules offers substantial reductions in emissions and energy savings [20, 27, 35]. This aligns with previous studies that highlight that aluminum and silicon production account for the largest share of lifecycle emissions in PV modules [18, 19]. Implementing effective recycling strategies would therefore not only reduce greenhouse gas emissions but also increase material recovery rates and lower the carbon intensity of future PV production [14, 15, 27]. Additionally, improving silicon recycling efficiency, a material with a relatively lower GWP reduction than aluminum, can further enhance overall system sustainability [29, 30, 34].

Third, technological feasibility assessments indicate that full recovery/direct reuse and mechanical recycling are the most practical approaches for Indonesia's current context. Both require relatively low investment and rely on technologies already available domestically, making them suitable for near-term implementation [24, 27, 28]. Similar approaches have been successfully applied in other developing economies, serving as an entry point for building more advanced recycling infrastructure over time [30, 34]. Conversely, chemical and laser-assisted recycling technologies, while offering higher material purity, require significant capital investment, advanced technical expertise, and environmental safeguards, and are currently barriers to their feasibility in Indonesia. These findings are consistent with earlier reports emphasizing the importance of aligning technology adoption with local industrial and economic capacity [21–23].

Finally, these technical insights must be accompanied by strong policy measures. The integration of recycling strategies into national renewable energy policy can be strengthened through Extended Producer Responsibility (EPR), fiscal incentives, and clear regulatory guidelines [31, 33]. Such instruments have been shown to accelerate the adoption of circular economy models in the PV sector internationally [32, 34]. Furthermore, collaboration among government, private industry, and research institutions will be essential to establish a sustainable PV waste management ecosystem that not only addresses environmental impacts but also stimulates green economic opportunities through resource recovery and job creation [16, 25, 26].

In practical terms, the findings of this study can inform the development of a structured national framework for PV waste management in Indonesia by integrating technological, regulatory, and economic instruments. The implementation of full recovery and mechanical recycling can be applied in both centralized and decentralized waste management schemes, supporting rural electrification, second-life markets, and material recovery industries [24, 27, 28, 34]. This approach not only reduces the environmental footprint of the solar energy sector but also creates economic opportunities through resource valorization and job creation in the circular economy ecosystem [16, 31, 33]. The study contributes to the literature by providing Indonesia-specific LCA-based evidence on PV waste management options, bridging the gap between global research and local implementation contexts [14, 15, 18, 25, 26]. Furthermore, integrating Extended Producer Responsibility (EPR), fiscal incentives, and local technology adaptation could enhance the scalability of PV recycling, as seen in successful models in the European Union and China [31–33]. For future research, a more comprehensive techno-economic analysis is needed to assess the financial viability of advanced recycling technologies such as chemical and laser-assisted processes in Indonesia's industrial landscape [28–30]. Integrating these with predictive waste modeling and regional material flow analysis can support better infrastructure planning and policy design [21–23, 35]. Additionally, exploring synergies among PV recycling, renewable manufacturing industries, and green financing mechanisms may help accelerate the country's path toward a low-carbon circular economy [1, 2, 6, 16, 27]. These directions will ensure that the transition to renewable energy in Indonesia not only meets emission-reduction targets but also builds a sustainable, resilient green industry base for the future.

4. Conclusions

This study sets out to evaluate the environmental impacts of monocrystalline PV panels throughout their life cycle and to identify feasible recycling strategies tailored to Indonesia's context. Using a LCA framework, the analysis compared landfill and recycling scenarios through two key environmental indicators, GWP and CED. The research also assessed different recycling technologies in terms of technical feasibility, economic viability, and alignment with local market and policy conditions.

The findings demonstrate that the rapid growth of PV installations in Indonesia, projected to exceed 8.5 GW by 2030, will generate over 1 million tons of panel waste by 2050. Recycling scenarios provide clear environmental advantages, with aluminum recovery reducing GWP by up to 83% and CED by up to 95% compared to primary production. Among various methods, full recovery/direct reuse and mechanical recycling emerged as the most feasible near-term strategies due to their lower investment costs, technical simplicity, and existing local capacity. Advanced methods such as chemical or laser-assisted recycling offer additional potential but require significant technological support and investment. An unexpected finding of this study was the magnitude of impact reduction achieved through aluminum recycling, which proved to be even more significant than initially anticipated. Furthermore, improvements in panel efficiency and extended operational lifespan substantially accelerated carbon payback time, underscoring the synergistic effect of combining waste management strategies with technological upgrades. The novelty of this work lies in providing Indonesia-specific, LCA-based evidence for PV waste management, bridging the gap between global research and national policy needs.

Unlike many existing studies conducted in developing countries with mature recycling infrastructure, this study explicitly considers Indonesia's local market dynamics, regulatory readiness, and technology availability. Some discrepancies were observed when comparing the theoretical efficiency of advanced recycling technologies with their realistic implementation potential in Indonesia. While chemical and laser-assisted methods promise higher material recovery rates, practical barriers such as capital intensity, technological readiness, and environmental compliance limit their near-term feasibility. This highlights the importance of adaptive policy instruments that balance environmental ambitions with local capabilities.

Future research should focus on detailed techno-economic assessments of advanced recycling technologies, integration of PV waste flows into national circular economy models, and predictive waste mapping to optimize infrastructure planning. It is also essential to explore policy mechanisms such as Extended Producer Responsibility (EPR) and green financing to enable large-scale adoption. The implications of these findings are significant: integrating recycling strategies with renewable energy policy will not only minimize environmental impacts but also strengthen Indonesia's green industry, support net-zero emission targets, and enhance energy transition resilience.

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