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A Lifecycle-Based Framework for Optimizing Photovoltaic Waste Management in Malaysia: Environmental and Economic Evidence from Kedah, Malaysia

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Abstract: The accelerated deployment of photovoltaic (PV) systems in Malaysia has raised critical concerns regarding end-of-life (EOL) panel waste, particularly in states like Kedah where large-scale solar installations are concentrated. Despite growing attention to solar energy, limited infrastructure and governance mechanisms exist for managing decommissioned PV panels. This study presents an integrated approach to optimizing EOL PV waste management in Kedah, Malaysia, by incorporating lifecycle-based environmental and economic analysis. With a projected increase in PV waste by 2034 and beyond, the research applies a combination of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Multi-Criteria Decision Analysis (MCDA), and Geographic Information Systems (GIS)-based modeling to assess and optimize each phase of the waste management process from uninstallation, transportation (T_1 and T_2), and collection center operations to recovery facilities (RF). Results show that optimized routing, strategic load consolidation, and selective frame dismantling at collection centers (CC) can reduce transport related emissions by up to 35% and operational costs by over 20%. The integration of Circular Economy (CE) principles and Extended Producer Responsibility (EPR) frameworks ensures material recovery (aluminum and silicon), improves traceability, and aligns the model with national regulatory standards. This research proposes a scalable, policy-aligned optimization framework that enhances environmental performance and cost efficiency in Malaysia's emerging PV waste sector.

Keywords: Optimize; End of life; Photovoltaic; Waste management; Kedah

1 Introduction

The global solar photovoltaic (PV) market continues to expand rapidly due to the global transition toward renewable energy, ambitious climate targets, and solar panel cost reduction [1]. From 2015 through 2023, the total PV capacity more than tripled as it got to over 1,200 GW on a worldwide scale [2]. Exponential growth in manufacturing capacity has caused a 50% reduction in PV panel prices, thereby increasing penetration in both large- and small-scale applications [3]. Among of others renewable energy, solar show the fastest development due to technology deployment, supporting policies, innovation in technology and other factors. Entire solar industries contribute a significant impact to this development. A critical concern for sustainability has emerged along with this growth like the projected volume of end-of-life (EOL) PV waste. Global PV module waste is projected to range from 8 to 78 million tonnes annually between 2030 and 2050 [4]. Recycling efforts remaining lagging may cause this to escalate up to approximately 60–78 million tonnes yearly by 2050. Figure 1 illustrates the leading global companies involved in solar panel recycling and EOL PV waste recovery, highlighting the international market landscape and the growing industrial ecosystem supporting circular PV waste management. These companies collectively hold the largest market share and dictate industry trends.

Figure 1. Leading companies in the solar panel recycling market

PV modules are made up of glass (76%), aluminum (8%), plastic (10%), silicon (5%) and metal (1%). The composition metal consists of lead and cadmium. These toxic leachates may contaminate soil and water if EOL is not properly treated [5, 6]. Since cadmium compounds can be hazardous to fish and wildlife and can impact humans via the food chain, these are forbidden in many countries [7].

The handling procedure is the main issue associated with the increasing amount of solar waste; improper management could result in these panels ending up in landfills and causing environmental problems [8]. If solar panel waste is not managed properly, it could build up and be thrown away in ways that aren't safe, which could lessen the environmental benefits of solar energy [3]. This concern is further supported by previous studies showing that improperly disposed modules may release harmful compounds into the environment [9]. Two prevalent techniques for managing solar panel waste are landfilling and recycling [10]. However, research on the feasibility of solar PV recycling plants remains limited, particularly in ASEAN countries [11].

Countries having advanced PV management policies depict successful models that follow the EU's WEEE Directive [6]. In Japan, extended producer responsibility (EPR) is implemented, module design for recycling is incentivized, and organized take-back systems are enforced [12]. Globally, research on managing PV solar panel is becoming a spotlight due to the amount of generated PV waste becomes significant. Most of the countries do a study related to the potential of PV solar waste generated. Previous projections estimated that EOL PV modules deployed in Spain in 2007–2008 would generate over 100,000 tons of cumulative waste between 2020 and 2030 [13]. However, Thailand is expected to produce at least 8,000 t of PV waste annually by 2030 [14].

Regardless of whether the current panels have lasted the whole 30 years, the researcher believe that logical consumers will switch if the cost of trading up is low enough and the efficiency and compensation rate are high enough [15]. As part of an entire EOL infrastructure that also involves uninstallation, transportation, and (in the interim) sufficient storage facilities for solar waste, the required capacity for recycling solar panels must be developed [15]. There is a study in Thailand to clarify the potential financial and environmental benefits of recycling solar panels. It estimates the cost to recycle could be as little as \$0.03 per kg [14]. However, according to a National Renewable Energy Laboratory (NREL) research, the cost of recycling a single solar module range from \$15 to \$45 [16].

Still, there has been limited evaluation of their environmental suitability in terms of lessened effects over the entire supply chain, and the few studies that are available usually solely focus particular recycling-related topics [17]. For example, this paper study the technical potentially and economic feasibility of solar system waste precisely PV waste management in Bangladesh [18].

In Malaysia, the PV industry grew as mandated in the National Energy Transition Roadmap (NETR), and Kedah developed important utility and distributed PV installations. Recently, Kedah has had one of the highest solar panel installations in Malaysia. However, Life Cycle Assessment (LCA) research within Malaysia has been quite limited, and researchers still have yet to investigate all EOL management phases. National regulations address PV waste not specifically, and most panels still go into landfills. Stakeholder preparedness along with potential resource loss with some gaps for environmental risk management are exposed. Previous international studies have investigated PV EOL waste management from environmental, economic, and policy perspectives. Table 1 summarizes representative studies, their methodological focus, major findings, and unresolved gaps that motivate the present lifecycle-based framework.

Table 1. Summary of previous studies on photovoltaic end-of-life waste management: focus, findings, and research gaps

Study/Region	Focus Methodology	Key Findings	Limitations/Gap
[5]	PV EOL, circular economy strategies	PV panels contain valuable & hazardous materials	Did not evaluate logistics or cost addition
[6]	Review of recycling methods	Identified risks of lead & cadmium leaching; recovery potential	Focused only on recycling, no economic analysis
[17]	LCA of recovery process	Showed environmental benefits of recycling	Limited to one recovery route, no cost evaluation
[14]	Environmental & economic impacts of PV waste	Highlighted trade-offs between recycling & disposal	Country-specific; no GIS /logistics modeling
[12]	Policy: EPR for CdTe modules	Incentives for recycling-oriented design	Technology-specific; no lifecycle economic view
[9]	Policy & regulations for PV waste	Need for regulatory framework	Limited practical case studies
[8]	Solar waste awareness & policy gaps	Identified urgent need for national system	Focused on policy; no lifecycle modeling
[18]	Techno-economic assessment	Noted high costs & limited infrastructure	Did not integrate LCA with cost analysis
[11]	Feasibility of mechanical recycling	Showed low-cost recycling possibility	Small-scale; lacks systemic modeling

Note: PV = Photovoltaic; EOL = End-of-Life; LCA = Life Cycle Assessment; EPR= Extended Producer Responsibility; GIS = Geographic Information Systems.

1.1 Theoretical Framework

This study adopts two interrelated theoretical frameworks which are, (i) the CE and (ii) EPR. The CE model promotes resource efficiency through recovery, reuse, and recycling of materials, aiming to decouple economic growth from resource consumption and environmental degradation [19, 20]. This principle is especially relevant for managing EOL solar panels, which consist of high-value materials such as silicon, aluminum, and silver, as well as hazardous components like lead and cadmium. The EPR framework shifts waste management responsibility from governments to producers [21]. It provides a policy lens through which producers and other stakeholders are held financially and logistically accountable for the post-consumer phase of PV modules. By embedding this principle into the optimization strategy such as enabling traceability, adhering to ISO 14001 environmental standards, and ensuring safe transport and dismantling, this study aligns with both international best practices [22] and local regulatory mandates from the Department of Environment (DOE) in Malaysia. Together, these frameworks underpin the development of an optimized, environmentally responsible, and economically viable PV waste management model. Figure 2 illustrates the conceptual framework graphic in this study.

This study recommends a comprehensive model-based guide for Kedah that maximizes the disposal of EOL PV waste. Data from 49 PV sites integrates due to LCA, cost evaluation, and Multi-Criteria Decision Analysis (MCDA). The study normalizes cost indicators and environmental emissions. Following this normalization, it provides predetermined perceptions into phased EOL interventions. By aligning PV decommissioning with global best practices and CE goals, it contributes to the advancement of Malaysia's capabilities. The remainder of this paper is structured as follows. The next section are details the methodology, including system boundaries, data collection, and analytical assessment. Section 3 presents and discusses the results of the environment and economic assessments, highlighting optimization strategies for PV waste management. Finally, Section 5 concludes the study and provides several implications together with recommendations for future research.

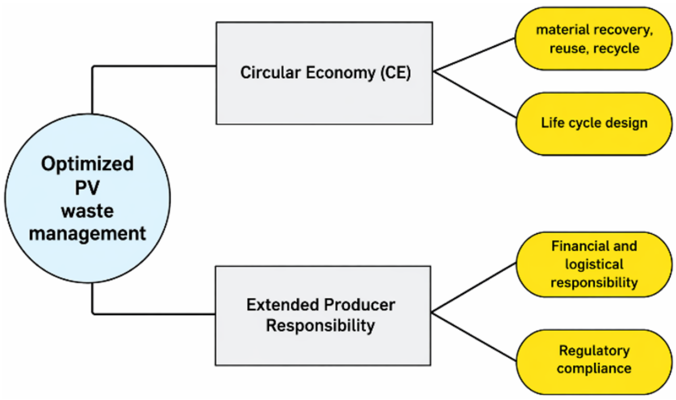


Figure 2. The conceptual framework graphic in this study
Note: PV = Photovoltaic

2 Methodology

This study focuses on the entire PV waste management chain in Kedah, consisting of solar panel generation source, transportation to collection centre (T_1), collection centre, transportation to recovery centre (T_2) and recovery facility. Figure 3 the system boundary applied in this study.

Figure 3. System boundary applied in this study

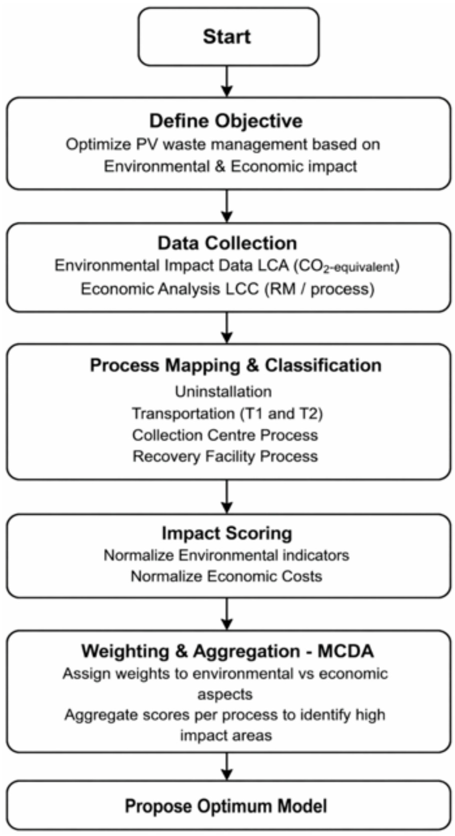


Figure 4. Research flow diagram
Note: LCA = Life Cycle Assessment; LCC = Life Cycle Costing; MCDA = Multi-Criteria Decision Analysis.

Figure 3 show the system boundary applied in this study environment and economic analysis are carried out based on the validated baseline results from the authors' previous lifecycle analysis study. The system boundary in this study was established to encompass solely the downstream or EoL phase of PV panels in accordance with ISO 14040 and 14044 standards. Panel removal, transportation to collection centre (T_1), the collection centers (CC), transportion to recovery facilities (RF) (T_2), and final material recovery are all included in the boundaries, as shown in Figure 3. The study's goal of enhancing waste handling and recovery procedures in Malaysia, where institutional and infrastructure support for EoL management is still scarce, is reflected in its emphasis on this "cradle-to-recovery" scope. Manufacturing and electricity generation processes were not included because they have previously been extensively studied in previous studies [23]. By focusing just on post-use management, the studies identify the processes that are most significant to Malaysia's current economic and regulatory issues. Figure 4 illustrates research flow diagram for this study.

2.1 Data Collection

Primary data were obtained from 49 PV system sites in Kedah, including capacity (MW) reported by the Energy Comission Malaysia, number of panels, weight, and spatial distribution. Data obtained covered the period from January 2023 to March 2024, indicate that the dataset reflects the most recent operational and PV systems in the region.

Environmental impact data were analyze using OpenLCA database, while economic inputs were collected from field interviews (e.g., Akshani Recovery Facility), and industry references. Table 2 listed the stakeholders and information source in PV waste management. Figure 5 shows cases the primary industry stakeholders directly involved in various phases of PV waste management in Kedah, Malaysia. These include Renosun Sdn. Bhd. and Enerco Engineering Sdn. Bhd., which are responsible for uninstallation of EoL solar panels; Trash4cash (M) Sdn. Bhd., operating as a collection centre; and Akshani Sdn. Bhd., serving as a recovery facility. These entities were engaged through direct site visits or interviews and represent critical links in the waste flow from disassembly to material recovery.

Table 2. Overview of stakeholders, functional roles, and information sources in photovoltaic waste management governance

Stakeholder	Role	Resources
Government (DOE)	Regulates waste licensing, transport, eSWIS	DOE website, guidelines
Industry (CC and RF)	Operates recovery, dismantling, and material separation	Primary interview
Academia	Develops LCA methods, innovation in dismantling	Literature reference
Local Authorities	Local enforcement, logistics coordination	DOE circulars
Informal Sector (NGOs)	Awareness, early-stage collection	E-waste policy reviews

Note: LCA = Life Cycle Assessment; DOE = Department of Environment;CC = collection centers; RF = recovery facilities.

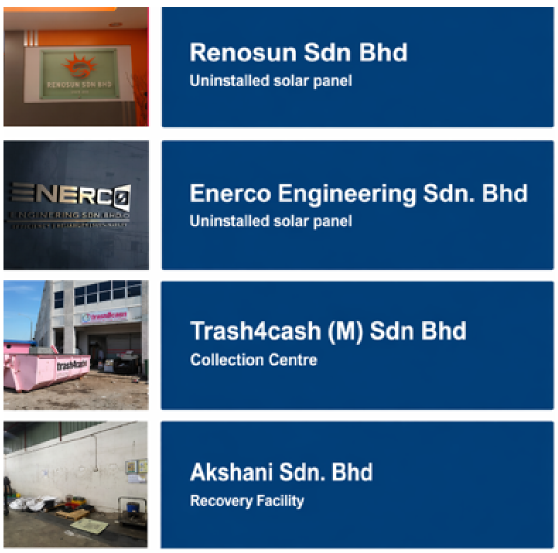


Figure 5. Primary industry stakeholders identified through field visits and interviews

To strengthen data quality, several measures were applied. Information from DOE reporting, industry provider records, and published references was cross-checked to ensure consistency. All datasets were standardized to a common functional unit (per panel or per kilogram of PV waste). Preprocessing steps, including unit harmonization and min–max normalization, were carried out to allow fair comparison across environmental and economic indicators. These steps improved the reliability of the integrated framework.

2.1.1 Life Cycle Assessment

The LCA methodology was employed to quantify the environmental impacts associated with each process of the PV waste management system from panel uninstallation to facility recovery. The study followed the ISO 14040 and ISO 14044 standards for LCA, and all modeling was executed using the OpenLCA software (version 1.11), coupled with the Ecoinvent 3.6 database for background data. The evaluation in this study was conducted in a series of steps: (i) identifying the functional unit; (ii) setting up the system boundary; (iii) collecting primary inventory data from 49 PV sites along with secondary datasets; (iv) applying the IPCC GWP100 and other impact categories; (v) normalizing the results using a min–max approach; and (vi) interpreting the most important processes prior to integrating them with Life Cycle Costing (LCC) and MCDA analyses.

The functional unit was defined as the treatment of 1 kg of EoL crystalline silicon PV panel waste. The system boundary followed a "cradle-to-recovery" framework, encompassing five primary processes: (1) source panel generation at the source, (2) transportation to the collection center (T_1), (3) collection center, (4) transportation to the recovery facility (T_2), and (5) recovery facility. In this study, to optimize the result, global warming potential (GWP100) was used with the unit kg CO_{2-eq}uivalent. Inventory data were obtained from primary field visits and DOE databases, as listed in Table 2. Emissions from transportation (T_1 and T_2) were calculated based on real routing distances extracted from GPS coordinates using QGIS mapping. Road distances were calculated using the GPS coordinates of each PV installation site for the transport phases (T_1 and T_2), and the shortest routes were then processed using QGIS network analysis. The distance traveled (kilometers), the payload transported (tons of PV waste), and the associated emission factor from the Ecoinvent 3.6 transport datasets (kg CO_{2-eq} per tonne-kilometer) were then combined to estimate emissions using an activity-based approach. The emission relationship was adapted from established IPCC greenhouse gas inventory guidelines [24]:

$$GWP_{trip} = \text{Distance}_{km} \times \text{Payload}_t \times EF_{tkm} \tag{1}$$

Load factors (LF), which express the effective payload as Payload_t = LF × Vehicle Capacity_t, were applied to partial loads and return trips in order to better reflect operating procedures. In order to ensure conformity with the LCA framework, the computed trip emissions were finally assigned to the functional unit by dividing by the carried PV mass (kg).

2.1.2 Life Cycle Costing

Complementing the LCA, a LCC approach was used to evaluate the economic feasibility of each PV waste process. The LCC covered the same five lifecycle process and adopted a bottom-up costing methodology. All monetary values were calculated in Malaysian Ringgit (RM) and reported in 2025 price levels.

The cost structure included:

•Uninstallation Costs: Labour, equipment rental, technician deployment (RM180–RM278.95 per panel)

•Transport T_1 and T_2: Fuel, toll, vehicle depreciation, and documentation (e.g., eSWIS, SW110), scaled by lorry type and trip distance

•Collection Centre Operation: Land rental, storage, labor, IV testing (RM2,500–RM3,000/month per tonne)

•Dismantling Costs: Manual vs. automated frame removal systems (RM3,000–RM6,000/month)

•Recovery Costs: Sorting, crushing, compliance, emissions control systems

LCC outputs were also normalized using a min–max scale and integrated with the LCA scores through a MCDA matrix. Sites and processes with high cumulative costs were flagged as financial bottlenecks, while low-cost/high-efficiency nodes were recommended for replication.

2.2 Normalization and Scoring

All environmental (LCA) and cost (LCC) indicators were normalized using the min–max method to enable comparison across different scales. The normalized value for each process or site was calculated as shown in Eq. (2):

$$N_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{2}$$

where, N_i is the normalized score, X_i is the actual value for process/site i, and $X_{\min}$ and $X_{\max}$ represent the minimum and maximum values observed in the dataset, respectively. This ensures all scores are scaled between 0 and 1, making environmental and cost indicators directly comparable within the MCDA framework.

Each site received a total score computed as the average of normalized environmental (NRMLZ_ENV) and cost scores (NRMLZ_COST). Eq. (2) used to calculate the total score.

$$\text{Total Score} = \frac{NRMLZ_{ENV} + NRMLZ_{COST}}{2} \tag{3}$$

2.3 End-of-Life Phase Classification

The classification into five stages was determined by projecting the EOL years of PV installations in Kedah. The expected service life of crystalline silicon panels (25–30 years) was applied to installation records reported by the Energy Commission of Malaysia. Systems expected to retire within a similar timeframe were grouped into one stage to reflect clustered waste generation and to facilitate planning for collection and recovery infrastructure. Table 3 presents the classification of PV installation sites into five projected EOL phases based on their expected retirement years.The stages are: Stage 1 (2034–2036), Stage 2 (2037–2038), Stage 3 (2039–2040), Stage 4 (2041–2042), and Stage 5 (2043 and beyond).

Table 3. Classification of photovoltaic installation sites into five end-of-life phases (2034–2043)

Year	Number of Sites	Locations
2034	5	Kuala Kedah; Kuala Muda; Baling
2035	3	Pokok Sena; Kulim; Kuala Muda
2036	3	Kuala Muda; Pokok Sena; Kota Setar
2037	11	Kuala Muda; Langkawi; Kubang Pasu; Kota Setar; Kulim; Pendang
2038	13	Kubang Pasu; Kulim; Kota Setar; Bandar Baharu; Kuala Muda; Pendang
2039	1	Kota Setar
2040	3	Pokok Sena; Kuala Muda
2041	1	Kuala Muda
2042	5	Kuala Muda; Sik; Kulim
2043	4	Baling; Kuala Muda; Kulim

2.4 Optimization and Ranking

A MCDA framework was used in prioritizing the management of EOL PV waste at the site level. In this study, the MCDA was designed in order to integrate environmental impact with cost. A scheme of equal weighting of 50:50 was used for the two. This approach ensures that we balance both ecological concerns with economic concerns as we evaluate PV waste processes.

2.4.1 Normalization process

Each criterion was normalized using the maximum-value method, where the highest observed value in the dataset was set as the reference point (i.e., a score of 1.00), and all other values were scaled proportionally:

$$\text{Normalized Score} = \frac{\text{Raw value}}{\text{Maximum value}} \tag{4}$$

This normalization was applied separately to (1) Environmental scores derived from life cycle impact categories (e.g., global warming potential (GWP)) and (2) Cost scores representing LCC estimates for each site/year.

2.4.2 Composite score calculation

For each year, the composite total score was computed by averaging the normalized environmental and cost scores:

$$\text{Total Score} = \frac{\text{Score}_{ENV} + \text{Score}_{COST}}{2} \tag{5}$$

This score was then used to rank years according to their overall environmental-economic burden, guiding priority-setting for intervention. Equations for normalization (Eqs. (1) and (3)) and composite score calculation (Eqs. (2) and (4)) are now referenced to standard LCA/MCDA methods [25, 26].

2.4.3 Optimization indicators for collection centre

• Intake Volume Control

Storage duration was calculated as the difference between the date of receipt and the date of dispatch for each batch. The threshold of 180 days was adopted in accordance with Malaysia's DOE Scheduled Waste Guidelines

(SW110), which stipulate that hazardous waste cannot be stored beyond six months [24]. Monthly storage costs were calculated using previously established cost models [14]:

$$\text{Cost}_{\text{storage}} = A_{\text{used}} \times r_{RM/m^2} \times \text{utilities} \times \text{handling} \tag{6}$$

where, A_{used} is the floor area occupied (m^2) and r is the monthly rental rate per m^2. The ceiling of RM2,500/month reflects facility quotations and operational expense surveys in Malaysia's waste sector [14].

• Panel Sorting and Inspection

Recovery rate was computed as the ratio of panels classified as reusable to the total panels received, with a minimum target of 60%. This benchmark is consistent with reuse feasibility studies in PV waste management [6, 14]. IV test accuracy was calculated using standard classification accuracy metrics [27]:

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN} \times 100\% \tag{7}$$

where, TP = true positives, TN = true negatives, FP = false positives, and FN = false negatives. A threshold of $\geq$90% was adopted in line with IEC 60891 international testing procedures for PV devices [27].

• Structured Pallet Handling

Breakage rate was measured as the number of damaged panels divided by the total panels handled. A maximum of 2% was set following safe-handling recommendations from PV recycling case studies [5]. Ecotoxicity values were derived using OpenLCA (Ecoinvent 3.6 database) and expressed in kg 1,4-DB eq. The benchmark of $\leq$205.37 kg 1,4-DB eq corresponds to baseline impacts of the collection centre process calculated in this study.

• Frame Removal

Monthly labour cost was calculated as total working hours multiplied by the average local wage rate (RM/hour). A cap of RM3,000/month was chosen in accordance with Malaysian labour market data based on current Malaysian industrial wage benchmarks. Metal yield was computed as [28]:

$$\text{Yield}_{\text{metal}} = \frac{m_{\text{metal,recoverd}}}{m_{\text{metal,frame}}} \times 100\% \tag{8}$$

where, $m_{\text{metal,recovered}}$ is the recovered aluminium mass and $m_{\text{metal,frame}}$ is the estimated frame mass from module specifications. The target of $\geq$85% was adopted from recovery efficiency studies on aluminium in PV recycling [28].

• Digital Traceability (eSWIS and Barcode)

Audit compliance was measured as the proportion of requirements (manifest records, reporting frequency, traceability) met under DOE's eSWIS system. The target of 100% compliance is required under Malaysian hazardous waste regulations [29]. ISO 14001 renewal success was a binary indicator based on surveillance audit outcomes, in line with international environmental management standards [30].

• Automation in Sorting

Throughput was estimated as [31]:

$$\text{Throughput} = (\text{panels/hour}) \times (\text{hours/shift}) \times (\text{shifts/day}) \times (\text{days/month}) \tag{9}$$

with a minimum target of 1,000 panels/month, consistent with pilot automation studies in Southeast Asia [31]. Emission savings were calculated as the percentage reduction in GWP (kg CO_2 eq) relative to the baseline [28]:

$$\%\text{Saving} = \frac{GWP_{\text{baseline}} - GWP_{\text{optimized}}}{GWP_{\text{baseline}}} \times 100\% \tag{10}$$

A threshold of $\geq$ 10% was used to ensure improvements exceeded typical LCA uncertainty margins [28].

•Material Value Monitoring

Revenue from recovery was computed as [31]:

$$\text{Revenue} = \sum_i (\text{yield}_i \times \text{purity}_i \times \text{price}_i) \tag{11}$$

where, i represents aluminium, glass, copper, or silver fractions. Prices were obtained from Malaysian scrap market quotations during 2023–2024, yielding a target range of RM500–2,000/ton [32].

3 Results and Discussions

The state of Kedah was selected as a representative region for modeling optimized PV waste management due to its diverse mix of solar PV installations. The spatial analysis in Figure 6 illustrates the actual site mapping of PV panel generation sources, CC, and RF, which were geolocated using verified datasets. The coordinates of all installed PV systems were obtained from the Energy Commission of Malaysia (Suruhanjaya Tenaga), ensuring precise identification of generation hotspots. Meanwhile, the location of current and proposed CC was referenced directly from the DOE database, including operational CCs in Jitra (Green Resource Recovery) and Alor Setar (Trash4Cash). Five major RF were also mapped, namely Akshani Sdn. Bhd., Warmtech Sdn. Bhd., Thitec Technology, Innovasi Laman Sdn. Bhd., and Taiko Metals Recycle Sdn. Bhd.

This spatial distribution forms the basis for assessing transportation flows (T_1 and T_2), emission hotspots, and network efficiency across the PV waste lifecycle. The Figure 6 reveals clustering of RF near Kulim and Sungai Petani, while some solar panel generation sites are more widely dispersed across the northern and eastern districts. This imbalance necessitated an optimized logistics model that minimizes carbon emissions and transport costs, especially for remote sites.

Figure 6. Spatial mapping of photovoltaic waste management infrastructure in Kedah, Malaysia: Including generation sites, collection centres, and recovery facilities

3.1 Environmental and Cost Impact Analysis

A total of 49 PV installation sites were assessed through normalized cost and environmental indicators from LCC and LCA. Each site had been assigned to it a total impact score. The score was calculated as the average of its normalized environmental and cost scores. These scores reflect each site's burden relative to environmental and economic dimensions.

With peak priority for 2041 (score = 0.8897) along with 2042 (score = 0.6281), Figure 7 presents a bar chart of each year's average total score. Solar panels at EOL cause the heaviest projected burden economically and environmentally in all these years. The impact notably increases from the year 2040, and this stresses the need for a plan to tactically ramp up infrastructure and collect capabilities prior to this threshold. The years 2034 through 2037 stay within the low-priority scope (score < 0.02). Monitoring as well as preparatory planning need to ready. Kedah's EOL for solar panels will begin in 2034, involving a total of 122,175 solar panels from different locations: Baling (B2, B3), Kuala Muda (KM6, KM7), and Kota Setar (KS1). Total scores exist at several high-priority sites that were identified in greatly elevated amounts (Table 3). For indicating of critical zones for early intervention, S1 (2042) and KM2 (2041) registered total scores of 0.9749 and 0.8897 respectively as among the highest in the dataset, KS2 (2038) and KS8 (2037) reported 0.00011 and 0.00083 total scores, respectively, conversely suggesting recovery measures are of low urgency. Table 4 listed the selected PV sites with highest and lowest total normalized scores.

This disparity reflects the uneven distribution of PV waste potential across the distinct, driven by system size, component density, and localized cost factors.

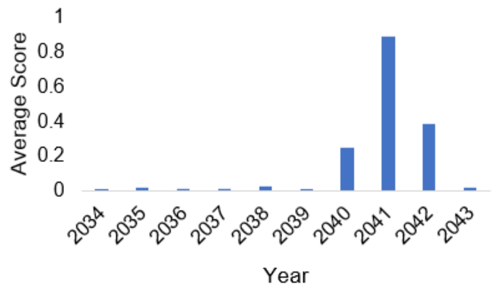


Figure 7. Cumulative average score

Table 4. Selected photovoltaic sites with highest and lowest total normalized scores

Site	Zone	Year	Norm_ENV	Norm_Cost	Total Score
S1	Sik	2042	0.9488	1.0010	0.9749
KM2	Kuala Muda	2041	1.001	0.7788	0.8897
KM1	Kuala Muda	2042	0.9699	0.7646	0.8672
KM3	Kuala Muda	2040	0.6397	0.49853	0.5691
KP1	Kubang Pasu	2038	0.2347	0.24442	0.2396
KS9	Kota Setar	2038	0.0009	0.00115	0.00104
KS10	Kota Setar	2038	0.0009	0.00112	0.00104
KS8	Kota Setar	2037	0.0007	0.00093	0.00083
KM15	Kuala Muda	2043	0.0002	0.00032	0.00023
KS2	Kota Setar	2038	0	0.00022	0.000110

3.2 Annualized Burden Ranking

To support time-based planning, total scores were aggregated annually to compute mean total impact per year, allowing for the identification of temporal hotspots. As shown in Table 5, the year 2041 recorded the highest average impact (Total Score = 0.8897), followed closely by 2042 (0.6281) and 2040 (0.5691). These years are projected to represent peak PV waste accumulation and processing demand, mainly due to the EOL of large-scale systems installed in earlier decades.

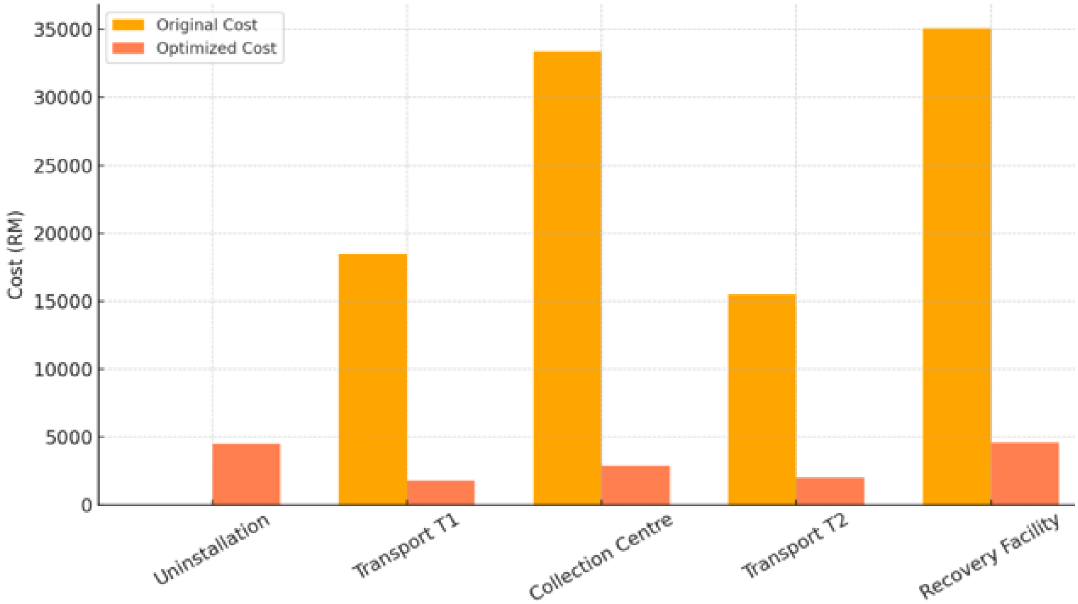
Table 5. Average total score by year (environment and cost combined)

Year	Average Total Score	Priority Level
2041	0.8897	Very High
2042	0.6281	High
2040	0.5691	High
2038	0.2396	Moderate
2037	0.1232	Low
2034–2035	$\leq$0.01	Minimal

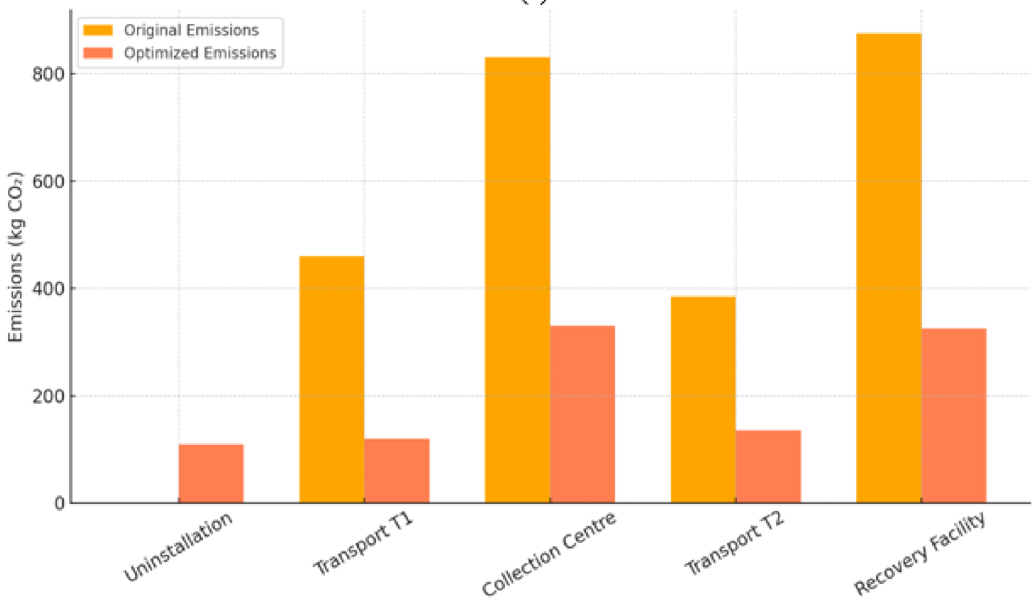
These findings suggest the need for staggered recovery infrastructure and resource allocation that aligns with projected PV waste surges.

3.3 Optimum Process Model for PV Waste Management

The optimum model for PV waste management proposed in this study integrated LCA, LCC, along with MCDA results. The optimization for the entire cycle of PV waste management is based on the normalization score for environmental and cost. In order to maximize recovery efficiency and to minimize environmental burden as well as to ensure economic viability, calculated responses were matched with the impact severity observed at each process. The model adopts a modular structure with scalability. It can handle both centralized and also decentralized PV waste across the varying years of impact intensity, and it ensures flexibility. Figure 8 compares the original and optimized versions of each analysis in terms of cost (a) and emissions (b). The optimized process shows lower costs across uninstallation, transport, collection, and recovery, mainly due to bulk scheduling, route consolidation, and automation. Emissions are also reduced, particularly in transport and collection centre operations, where improved logistics and reduced panel breakage limit greenhouse gas emissions and ecotoxicity. These results highlight that the optimized framework enhances both economic efficiency and environmental performance compared with the baseline.



(a)



(b)

Figure 8. Comparison of the original and optimized versions of each process for (a) cost and (b) emissions

3.3.1 Photovoltaic panel uninstallation

PV waste handling does begin with the important initial uninstallation process here. EOL panels must be safely removed without damage to valuable components like glass, silicon wafers, and junction boxes. For high-impact years, like 2041 and 2042, the model offers recommendations as below. For this process contribute 0.0054 kg CO_{2-eq}/kg of solar panel waste. While the cost for uninstalled solar panel and ready to transport are varies from RM 180 to RM 278.95 per solar panel. Table 6 presents the detailed optimization strategies for the PV panel uninstallation process, together with their respective operational targets and performance indicators related to time efficiency, labour utilization, panel protection, and digital traceability.

The optimization of the uninstallation process prioritizes efficient logistics, minimal panel breakage, with safe disconnection. It allows for a reduction of costs within that RM3,000 to RM4,500 range while it limits environmental impacts like CO_2 emissions plus ecotoxicity observed for transporting (T_1). These improvements align to best practices.

Table 6. Detailed optimization strategy for photovoltaic panel uninstallation process

Strategy	Target	Indicator
Standardized SOPs	Reduce time and breakage	Damage rate
Bulk scheduling	Lower mobilization cost	Labour efficiency
Skilled labour deployment	Reduce labour cost and error	Panel/Technician ratio
Pre-assessment of sites	Minimize complexity and delays	Pre-removal time
Technical to panel ratio	Balance workforce efficiency	Man hour per panel
Damage control equipment	Protect material during removal	Breakage %
Digital tracking via QR tags	Improve traceability & routing	Traceability

3.3.2 Transportation to collection centre (T_1)

The optimization of the Transport T_1 process, which involves the movement of EOL PV panels from generation sites to collection centres, is critical to reducing both operational costs and environmental impacts. Based on the normalized emission and cost data, emissions per kilogram of transported PV waste typically fall around 0.005352 kg CO_{2-eq}/kg, highlighting the importance of minimizing travel distances and improving load efficiency. One of the primary strategies for optimization is the use of Geographic Information Systems (GIS) to identify the shortest, least-congested routes between source sites and collection centres. By applying GIS-based routing in conjunction with linear programming techniques, transport schedules can be optimized for maximum payload and minimal redundancy.

Furthermore, the use of larger-capacity vehicles, such as 4-ton lorries capable of transporting up to 196 panels per trip, significantly reduces the number of journeys required. This not only lowers the cumulative CO_2 emissions but also compresses cost per trip, especially when cost per kilometre is targeted to remain below RM1.00. In regions where solar panel sources are spatially clustered such as within a 10 km radius, logistical consolidation of uninstalled panels into single batch loads is recommended. These batch transport strategies improve efficiency without increasing emissions disproportionately.

Additionally, adopting digital tools such as LCA calculators can support the estimation of carbon intensity per trip, and when integrated with inventory data, provide real-time monitoring of logistics performance. Key performance indicators (KPIs) should focus on limiting transport-related emissions to $\leq$0.0053 kg CO_{2-eq}/kg, maintaining costs at or below RM1.00 per kilometre, and ensuring that each lorry trip consolidates between 800 to 1000 panels to maximize value. Collectively, these measures contribute to a sustainable and cost-efficient model for the initial stage of PV waste logistics. Table 7 presents the detailed optimization strategies for transportation from PV source sites to collection centres (T_1), together with the corresponding operational targets and performance indicators related to routing efficiency, trip consolidation, vehicle utilization, and transport cost–emission trade-offs.

Table 7. Detailed optimization strategy for transportation (T_1)

Strategy	Target	Indicator
Route optimization using Geographic Information Systems	Minimize transport distance and fuel use	Distance per Trip (km)
Batch transport scheduling	Reduce number of trips and idle time	Panels per Trip
Use of high-capacity Lorries	Lower cost and emissions per panel	Cost per km (RM)
Consolidated collection from nearby sites	Maximize load efficiency across clustered sites	CO_2 per kg photovoltaic waste
Digital tracking and cost monitoring	Improve data visibility and reduce variability	Cost vs Emission Trade-off Ratio

3.3.3 Collection centre operations

One of the most important operational challenges is controlling the overall volume of all incoming solar panels. Excessive intake can overload storage spaces, cause processing delays, and raise the chance of panel breakage. The DOE only requires panel storage for 180 days since compliance depends on volume management. Ineffective systems could raise monthly storage expenses to RM2,500 per storage. Intake volume should match facility capacity. This alignment maintains both compliance and operational flow.

Recovery rates significantly increase when personnel accurately sort and check goods upon their arrival at the collection center. IV tests range in price from RM1,500 to RM3,000 to identify the reusable panels. An effective sorting process can reduce waste, and then the prospective revenue has increased. On the other hand, categorization leads to unnecessary disposal, which, according to LCA estimations, adds to a GWP of 0.6536 kg CO_{2-eq} per panel.

The way handling procedures are carried out has a direct impact on the environment. Operational expenses are also directly impacted by these approaches. Pallet stacking and the usage of foam separators reduce the chance of damage. Mishandling is linked to marine ecotoxicity levels of up to 205.37 kg 1,4-DB eq. The high marine ecotoxicity recorded for collection centre operations 205.37 kg 1,4-DB eq underscores the risk of heavy metal leaching due to cracked panels stored under inadequate conditions. Likewise, elevated human toxicity amount can be associated with potential dust exposure during manual approach, consistent with risks previously identified in the literature [5, 6].

Cutting down on breakage also lowers disposal expenses, which can range from RM1,000 to RM2,000 per panel.

This technology is essential to efficiency. The significant labor expenses associated with manual dismantling are anticipated to be between RM3,000 and RM6,000 per month. The hydraulic frame removal machines are used because they improve the quality, safety, and uniformity of the materials that are recovered. Aluminum, for instance, can sell for between RM500 and RM2,000 per ton. Automation also facilitates cleaner separation. Additionally, automation can lower emissions downstream.

Systems for traceability are in place so that activities remain visible and regulators can ensure compliance. Tracking of each panel is enabled for both barcode labeling and eSWIS registration integration. It costs between RM12,000 and RM15,000 a year to maintain ISO 14001 compliance, which makes legal reporting and audit readiness easier. The accuracy and efficiency of documentation are enhanced by digital records.

Table 8. Optimization matrix for collection centre process

Strategy	Target	Indicator
Intake volume control	Prevent overcapacity and reduce storage duration	Panels stored $\leq$ 180 days; Storage Cost $\leq$ RM2,500/month
Panel sorting & Inspection	Increase recovery of reusable panels and reduce disposal volume	Recovery Rate $\geq$ 60%; IV Test Accuracy $\geq$ 90%
Structured pallet handling	Minimize panel breakage and environmental toxicity	Breakage Rate $\leq$ 2%; Ecotoxicity $\leq$ 205.37 kg 1,4-DB eq
Hydraulic frame Removal	Lower manual dismantling cost and increase aluminium quality	Monthly Labour Cost $\leq$ RM3,000; Aluminium Yield $\geq$ 85%
Digital traceability (eSWIS + Barcode)	Ensure compliance and inventory control	Audit Compliance = 100%; ISO 14001 Renewal Success
Automation in sorting	Reduce labor dependency and increase throughput	Throughput $\geq$ 1000 panels/month; Emission Saving $\geq$ 10%
Material value monitoring	Track recovered material value (Al, glass, etc.)	Revenue from recovery $\geq$ RM500–RM2,000/ton

Figure 9. Interior design for collection centre

Optimal intake management, accurate inspection, sophisticated dismantling, trustworthy traceability, and effective logistics are all crucial components. These tactics are supported by Malaysian regulatory systems. These practices are consistent with international PV recycling recommendations [29]. These enhancements result in PV waste management systems that are more efficient and sustainable. Figure 9 show suggestion for interior design for collection centre. Table 8 lists the optimization matrix for this process. The intake volume control threshold was determined using the minimum-constraint method (see Section 2.4.3). Among the three factors considered with storage space capacity (≈1,400 panels), regulatory allowance under DOE SW110 (≈1,800 panels), and operational throughput with a 10-day buffer (≈800 panels), the most restrictive factor was throughput. Accordingly, the threshold was set at 800 panels, equivalent to four truckloads of 200 panels each. This ensures compliance with regulatory requirements while maintaining logistical efficiency. Figure 9 iliustrate the interior design for collection centre.

3.3.4 Transportation to recovery facility (T_2)

Transportation T_2 process, which connects the collection centres (CC) to RF, represents a critical link in the PV waste management value chain. Although each trip exhibits a modest environmental burden such as 0.007334 kg CO_{2-eq} of GWP (GWP100a), 0.0000428 kg SO_{2-eq} for acidification, and 0.00000862 kg PO_4^{3-}-eq for eutrophication, these impacts can accumulate over time. This is particularly relevant when underloaded trips, inadequate vehicle selection, or ineffective route scheduling lead to recurrent excursions.

To optimize the T_2 process, several strategies can be adopted. First, load consolidation plays a pivotal role. By grouping up to 800 panels per trip, organizations can maximize payload per trip, minimize frequency, and thus reduce both total emissions and cost. The removal of frames at the collection centre further enhances load efficiency by enabling denser stacking of panels, thereby reducing both weight and volume per trip.

Vehicle selection should be aligned with expected payloads and route distances. For instance, 1-ton or 4-ton lorries are ideal for small batches over short distances, while 10-ton or 32-ton lorries are preferable for high-volume regional transfers. Larger trucks, though less frequent, lower cost per panel and distribute emissions across more units, improving environmental performance.

Route optimization tools such as GIS and logistics software can further reduce travel distance, fuel consumption, and idle time. Additionally, packaging methods involving foam separators, padded pallets, and strap systems mitigate damage, preserving panel value and preventing costly breakage. Finally, digital compliance through eSWIS and SW110 documentation ensures legal traceability while maintaining audit readiness. By integrating these measures, the T_2 phase not only becomes more cost-effective but also significantly reduces its carbon footprint, supporting a more sustainable and efficient PV waste management system. Figure 10 summarizes the optimization strategy for transportation process.

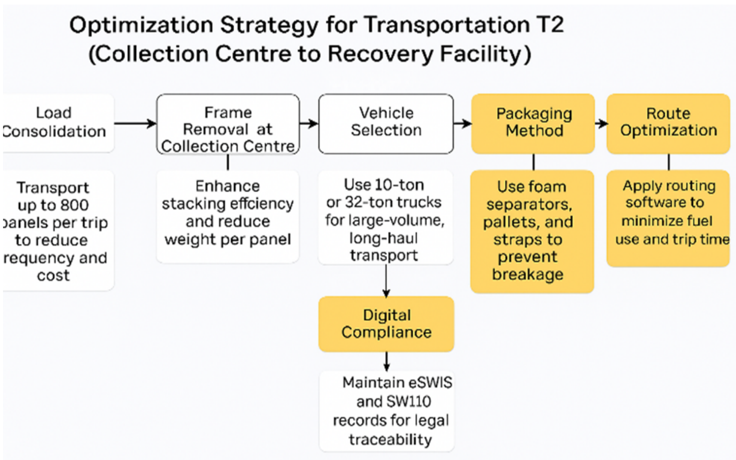


Figure 10. Optimization strategy for transportation process

3.3.5 Recovery facility process

The final process of PV waste management occurs at a recovery facility and plays a crucial role in maximizing material retrieval while minimizing environmental and economic impacts. According to environmental metrics drawn from the dataset, the recovery process contributes significantly to GWP, acidification, and eutrophication. Even though exact numbers are unclear because of some issues in the data, earlier emissions information indicates that this process can be the most harmful if not done properly, especially because it uses a lot of energy and doesn't separate materials completely.

To address this issues, several key optimization strategies can be adopted. The deployment of automated dismantling machinery such as hydraulic frame removers and laser glass cutters can substantially reduce human labor costs and improve material quality. These technologies not only reduce manual errors but also enhance yield rates for high-value materials like silicon wafers, silver, and aluminum. Previous studies have shown that improved material separation directly increases resale value and reduces downstream emissions [1, 29], improved material separation has a direct positive correlation with market resale value and downstream emissions reductions.

Thermal and mechanical preprocessing integration within the facility, supported by renewable energy where feasible, can mitigate emissions related to grid electricity use. The use of closed-loop water treatment and air filtration technologies can further reduce eutrophication and acidification contributions.

Economically, the cost elements from dataset highlight high administrative and operational costs (RM2,500–RM6,000 per batch). Cost efficiency can be improved through batch scheduling, maintenance standardization, and adoption of ISO 14001, compliant digital traceability systems that also fulfill DOE audit and legal documentation requirements (SW110, eSWIS). Table 9 presents the optimization matrix for recovery facility operations, outlining the key optimization areas, proposed strategies, decision support tools, and target KPIs associated with material recovery, energy efficiency, emission control, cost reduction, compliance, and resource value maximization.

Table 9. Optimization matrix for recovery facility process

Optimization Area	Strategy	Decision Support Tool	Target KPI
Material recovery	Use automated dismantling	Operational Automation Software	$\geq$85% material recovery rate
Energy use	Integrate renewable energy	Energy Management System (EMS)	Reduce global warming potential (GWP) to <0.005 kg CO_{2-eq}/panel
Emission reduction	Install air filtration, closed-loop water reuse	Environmental Monitoring System	Acidification & eutrophication minimized
Cost rfficiency	Schedule batch processing; reduce redundancy	Facility Management Software	Cost $\leq$ RM300 per panel
Labor optimization	Replace manual dismantling with semi/automated tools	SOP Auditing System	Reduce labor cost by 30–50%
Traceability and compliance	Maintain ISO 14001 traceability (eSWIS, SW110)	Compliance Management System	100% audit readiness and trace log
Resource value maximization	Separate high-value materials (Al, Si, Ag) cleanly	Smart Sorting & Tagging Tools	Maximize resale value (e.g., Al = RM500–RM2,000/t)

3.4 Optimization Guidelines for Photovoltaic Waste Management

A set of strategic guidelines was developed based on the total normalized scores for each EOL year. These scores, derived from site-specific LCA and LCC indicators, were averaged per year to identify temporal clusters of impact. The scores reflect the compounded burden from both environmental and economic dimensions and serve as a basis for staggered planning, logistics deployment, and infrastructure investment.

Figure 11 presents the spatial distribution of the proposed CC and existing RF across Kedah, Malaysia. The recommended collection centres in Jitra, Alor Setar, Sungai Petani, and Kulim are strategically positioned based on proximity to PV waste generation sites, existing infrastructure, and logistical accessibility. RF such as RF_Akshani, RF_Thitec Technology, and RF_Taiko Metal Recycle are co-located or in close range, enabling efficient Transport T_2 routing. This spatial configuration supports the cost- and emission-optimized waste management model proposed in this study.

Table 10 presents the operational guideline matrix for PV waste management based on priority class, linking total score ranges with recommended actions, implementation justifications, and representative site categories to support staged infrastructure and logistics planning.

Figure 12 shows the heatmap illustrates the distribution of PV source locations in Kedah based on their normalized total scores, which combine both environmental and economic impacts. Sites with higher total scores indicated by warmer colors represent priority areas for immediate optimization interventions due to their potential contribution to increased waste and emissions if unmanaged. This infographic (Figure 13) maps the optimized layout of the PV waste management system in Kedah, including identified PV source sites (blue dots), proposed collection centres (orange triangles), and designated RF (green squares). The spatial arrangement supports cost and emission minimized logistics planning by ensuring proximity between PV sources, collection points, and processing infrastructure, thus reinforcing CE principles in regional waste handling.

Figure 11. Optimized locations of collection centres and recovery facilities in Kedah

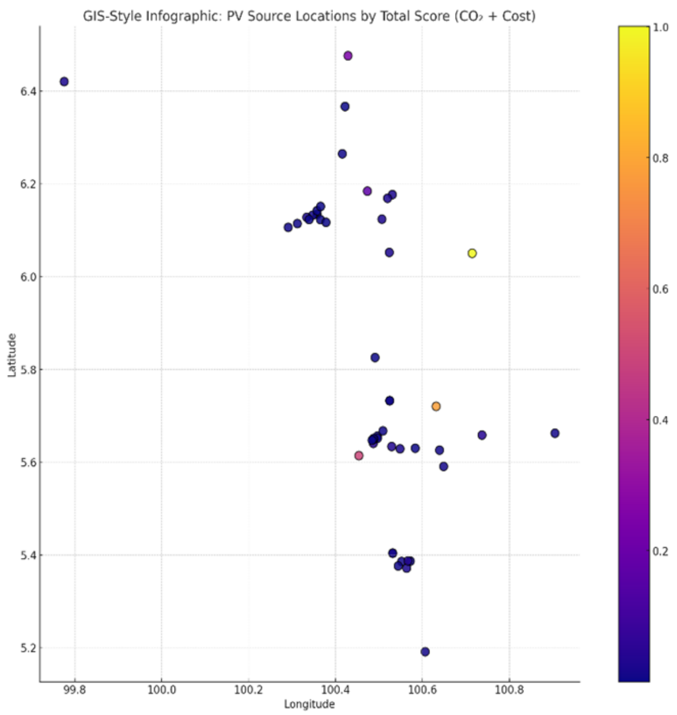


Figure 12. Geographic information systems-style infographic of photovoltaic source locations based on normalized total score

Table 10. Operational guidelines for photovoltaic waste management by priority class based on total normalized scores

Priority Class	Total Score Range	Guidelines Action	Justification	Site
Very high priority	≥0.70	•Establish fixed recovery hubs in high-density districts (e.g., Kuala Muda) •Secure logistics fleet (e.g., 32-ton lorry routes) •Early budgeting for high recovery and disassembly volume •Monthly recovery targets and forward contracts with licensed recyclers •Use GIS-optimized transport to reduce per-ton carbon footprint and fuel cost	•High normalized ENV due to mass >2.4M kg •High-cost impact due to long distance + complex dismantling	•KM2 •S1
High priority	0.40–0.70	•Semi-permanent mobile centres for sorting and panel classification •Phased deployment of storage and disassembly facilities •Panel reuse checks (IV testing) to filter viable units before recovery •Include in DOE reporting schedule for targeted inspections	•Sites are moderately large (e.g., >73,000 panels per year) •Cost impact moderate due to partial manual disassembly feasibility	•KM3 •KM14
Moderate priority	0.10–0.40	•On-demand mobile collection by e-waste contractors •Use shared logistics with other districts •Train local operators for basic sorting and packaging •Integrate collection with community-based recycling initiatives	•Sites are small-to-medium (5,000–30,000 panels) •Costs are lower due to nearby facilities and manual processes	•KP1 •KM9
Low priority	≤0.10	•No new infrastructure needed •Delay action until combined with future high-priority shipments •Use e-waste routes for shared transport and packaging •Passive monitoring only, no immediate policy intervention	•Very low mass and site-level impact •Not economically feasible for independent recovery setup	•KS2 •KM15

Note: GIS = Geographic Information Systems; DOE = Department of Environment; ENV = environmental; KS = Kota Setar; KM = Kuala Muda.

High Total Scores reflect combined economic and environmental burden, warranting immediate mitigation. Early phase locations often had higher capacity and centralized proximity to CC, amplifying their impact. Key recovery costs included labor (RM250–350/panel), disposal (RM38/ton), and audit compliance (RM12,000/year).

Figure 14 illustrates the framework for optimized PV waste management. The framework for optimized PV waste management integrates across all key lifecycle phases that range from decommissioning sources to planned recovery interventions that design cost and impact reductions. It begins when protocols for safety with strategies to minimize damage guide processes for site-specific uninstallation, and optimized routing and vehicle selection efficiently transport T_1 to collection centres located tactically. Dismantling and sorting occur in a semi-automated way at the collection centres. Because of those processes, material recovery and tracking accuracy improve. Nearest RF will then connect to T_2 transport. It is planned that the carbon footprint for this transport is to be lowest. Decision support tools such as LCA, MCDA, as well as GIS mapping, can inform as well as simulate best-case routing and facility placement. This structured system aligns with the CE principle, which emphasizes material recovery, reuse, and lifecycle-based design as seen in the dismantling strategies and high material yield targets (>85%) at RF. At the same time, the EPR framework is operationalized through traceability systems (e.g., eSWIS, QR inventory) and ISO 14001 compliance mechanisms, ensuring producers and handlers are financially and logistically accountable for EOL management of solar panels. Implementation is strengthened through policy compliance, stakeholder engagement, also each phase's measurable KPIs like cost per panel, CO_{2-eq} emissions, also recovery efficiency in order to ensure alignment to national sustainability targets and ISO 14001 standards. By embedding CE and EPR principles, the framework not only ensures environmental integrity but also creates a governance pathway for long-term circularity and compliance in Malaysia's PV waste sector. Compared with conventional single-focus approaches, the integrated framework applied in this study provides several advantages. Previous works have often addressed recycling or material recovery processes [17], or considered only the economic dimension [14]. In contrast, this study combines LCA, LCC, MCDA, and GIS-based routing, thereby enabling simultaneous evaluation of environmental impacts, economic costs, and spatial efficiency. This broader scope is consistent with the standard [30], which highlights the need for comprehensive EOL strategies for PV systems. The framework was applied to empirical data from 49 PV sites in Kedah, demonstrating that the method is not only conceptually robust but also practically verifiable through real-world operational data.

Figure 13. Geographic information systems-style infographic of optimized photovoltaic waste management system layout in Kedah

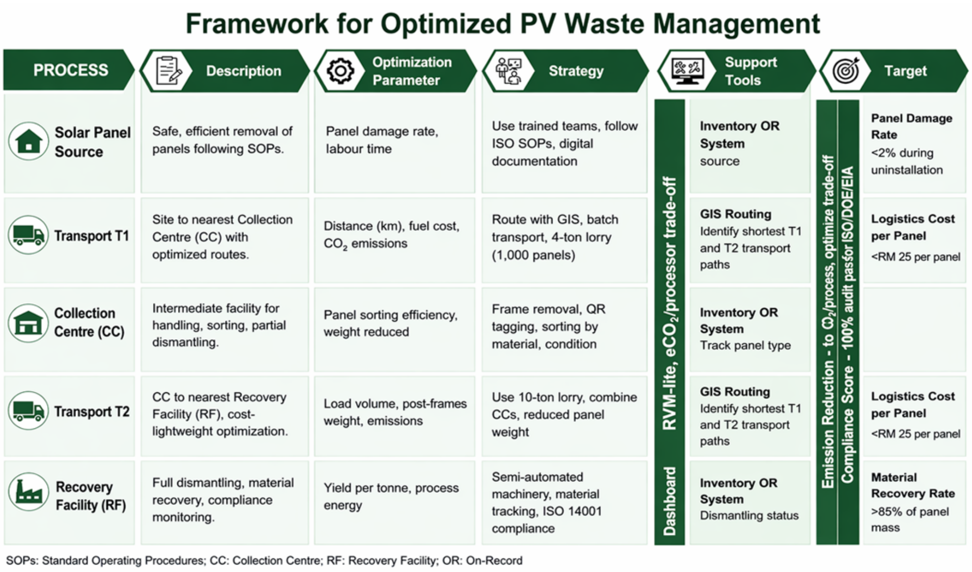


Figure 14. Framework for optimized photovoltaic waste management

4 Conclusion

This study has developed a comprehensive, data-driven framework for optimizing PV waste management in Kedah, Malaysia, through the integration of environmental and economic lifecycle analyses. By evaluating 49 PV sites using LCA, LCC, and MCDA, the research identifies targeted strategies for reducing both carbon emissions and operational costs across all key phases: uninstallation, transportation (T_1 and T_2), collection, and recovery. The findings highlight the effectiveness of bulk scheduling, load consolidation, automation at CC, and spatial optimization using GIS in achieving substantial gains in material recovery and cost efficiency.

The inclusion of CE principles such as resource circularity, reuse, and recycling and the application of EPR through traceability and compliance mechanisms (e.g., ISO 14001, eSWIS) ensure that the model is both environmentally sustainable and aligned with Malaysia's regulatory landscape. The proposed optimization framework is not only adaptable and scalable but also provides a policy-relevant tool for national PV waste management planning. Future work may focus on incorporating stakeholder behavior and real-time data analytics to further refine decision-making across regions.

Author Contributions

S.M.S. carried out the main conceptualization, methodology, field verification, data analysis, lifecycle assessment, cost modeling, GIS-based optimization, framework development, figure preparation, and manuscript drafting. The co-authors contributed through review, comments, and overall feedback to improve the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

CE	Circular economy
EOL	End of life
EPR	Extended Producer Responsibility
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCDA	Multi-Criteria Decision Analysis
PV	Photovoltaic
T_1	Transportation to Collection Centre
T_2	Transportation to Recovery Facility