International Journal of Renewable, Green, and Sustainable Energy (IJRGSE)
eISSN: 3087-4300
Volume03 Issue07 | Page No: - 01-07

Received: 28 May 2026, Revised: 17 June 2026, Accepted: 22 June 2026, Published: 06 July 2026

DOI: https://doi.org/10.55640/ijrgse-v03i07-01

Sustainable Management of Photovoltaic Waste in Malaysia: A Comprehensive Review of Current Practices and Future Directions

Kwame Mensah [1], Ama Osei[2]

[1] Department of Renewable Energy Engineering, University of Energy and Natural Resources, Ghana

[2] School of Environmental Science and Sustainability, Accra Institute of Technology, Ghana

ABSTRACT: The rapid expansion of solar photovoltaic (PV) deployment in Malaysia has significantly contributed to national renewable energy targets and decarbonization strategies. However, this growth has simultaneously generated an emerging environmental challenge associated with end-of-life (EoL) PV waste management. Photovoltaic modules contain valuable materials such as silicon, silver, aluminum, and rare metals, but also hazardous components that require controlled handling. This paper provides a comprehensive review of sustainable photovoltaic waste management in Malaysia, synthesizing global recycling practices, life cycle impacts, and policy frameworks to identify gaps and future directions for circular economy integration. Drawing on comparative international literature, the study highlights the importance of integrating physical and chemical recycling methods, improving regulatory enforcement, and establishing structured reverse logistics systems. Prior studies emphasize that inadequate PV waste governance can lead to long-term environmental burdens and resource inefficiencies, particularly in developing countries (Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145). The findings suggest that Malaysia's current e-waste framework requires enhancement to address the projected increase in solar panel disposal. The study concludes that a transition toward circular economy-based PV waste management is essential for achieving long-term sustainability in the renewable energy sector.

KEYWORDS: Photovoltaic waste, Malaysia, solar panel recycling, circular economy, renewable energy sustainability, e-waste management, life cycle assessment, end-of-life management, policy framework, resource recovery.

1. Introduction

1.1 Background of the Study

The global transition toward renewable energy has accelerated the adoption of solar photovoltaic (PV) systems as a key technology for reducing greenhouse gas emissions and dependence on fossil fuels. Malaysia, as part of its national energy transition agenda, has significantly increased solar PV installations across residential, commercial, and utility-scale applications. According to national energy statistics, renewable energy capacity continues to expand steadily, reflecting strong policy support and investment incentives (Energy Commission, 2023). While this expansion supports climate mitigation objectives, it simultaneously introduces a long-term sustainability challenge: the accumulation of photovoltaic waste.

Photovoltaic modules typically have a lifespan of 20–30 years. As early-generation installations reach end-of-life (EoL), Malaysia is expected to experience a significant rise in PV waste generation. This emerging waste stream contains valuable materials such as silicon, copper, and silver, which can be recovered through recycling processes. However, improper disposal may lead to environmental contamination and resource loss. The Department of Environment (DOE, 2022) highlights that Malaysia's existing e-waste management framework is primarily designed for general electronic waste and does not fully address PV-specific material complexities.

1.2 Problem Statement

Despite increasing PV deployment, Malaysia lacks a dedicated and integrated photovoltaic waste management system. Current practices are fragmented, with limited infrastructure for collection, dismantling, and material recovery. This creates inefficiencies in resource utilization and increases environmental risks associated with landfill disposal. Global research indicates that decommissioned PV modules represent a growing waste stream that requires urgent policy attention (Mahmoudi, S., Huda, N., & Behnia, M. (2021a).

Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145).

Furthermore, existing recycling technologies are often economically unviable without policy incentives or extended producer responsibility (EPR) systems. As a result, Malaysia risks facing a structural gap between renewable energy expansion and sustainable waste management capacity.

1.3 Research Objectives

This study aims to:

1. Examine current global practices in photovoltaic waste management.
2. Analyze Malaysia's existing e-waste and renewable energy waste framework.
3. Identify technological and policy gaps in PV waste handling.
4. Evaluate circular economy opportunities for PV material recovery.
5. Propose future directions for sustainable PV waste management in Malaysia.

1.4 Scope and Significance

This review focuses on photovoltaic waste management systems, recycling technologies, policy frameworks, and sustainability implications. It synthesizes findings from international case studies and applies them to the Malaysian context. The significance of this research lies in its contribution to bridging the gap between renewable energy deployment and waste sustainability planning. By integrating circular economy principles, Malaysia can enhance resource efficiency and reduce environmental impacts associated with solar energy infrastructure.

2. Literature Review

2.1 Global Perspectives on Photovoltaic Waste Management

Photovoltaic waste management has gained increasing attention due to the rapid global expansion of solar energy systems. Studies indicate that PV modules contain both valuable and hazardous materials, requiring specialized recycling techniques such as mechanical separation and chemical extraction (Azeumo et al., 2019). These processes enable recovery of silicon wafers, metals, and glass components, thereby reducing dependency on virgin material extraction.

Chowdhury et al. (2020) provide a comprehensive overview of end-of-life PV recycling systems, emphasizing the importance of integrated recovery chains that combine dismantling, sorting, and material purification. Their findings suggest that efficient recycling systems can recover up to 90% of module materials, although economic feasibility remains a challenge.

2.2 Life Cycle and Environmental Impact Assessments

Life cycle assessment (LCA) studies demonstrate that PV systems, while environmentally beneficial during operation, generate significant impacts at the disposal stage. Badza et al. (2023) highlight that large-scale solar PV plants in developing countries exhibit notable end-of-life environmental burdens if recycling systems are not implemented.

Similarly, Gönen and Kaplanoğlu (2019) emphasize that improper disposal of solar panels contributes to long-term environmental degradation, while structured recycling systems can reduce emissions and improve economic outcomes. These findings reinforce the necessity of integrating sustainability principles across the full PV life cycle.

2.3 Circular Economy and Resource Recovery Approaches

The circular economy framework has emerged as a key strategy for addressing PV waste challenges. Goh et al. (2024) propose a novel approach to recovering valuable elements from solar panels for use in construction materials, supporting waste valorization and climate resilience. This approach aligns with broader sustainability goals by transforming waste into secondary resources.

Innovations in recycling technologies further support circularity. Mechanical and chemical recovery processes allow separation of high-value materials, although efficiency varies depending on module type and degradation level (Azeumo et al., 2019).

2.4 Policy and Regulatory Frameworks

Policy interventions play a critical role in shaping PV waste management systems. Jain et al. (2022) analyze India's policy framework for solar PV waste and highlight the importance of extended producer responsibility (EPR) mechanisms. Similar policy gaps are observed in Malaysia, where e-waste regulations exist but are not PV-specific (DOE, 2022).

Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145, emphasize that OECD countries face increasing PV waste challenges due to insufficient regulatory preparedness. This insight is particularly relevant for

Malaysia, where policy frameworks are still evolving.

2.5 Technological Innovations in PV Recycling

Technological advancements are central to improving PV waste recovery efficiency. Choi and Fthenakis (2014) discuss macro and micro-level recycling planning for crystalline silicon PV systems, highlighting the need for optimized collection logistics and material separation processes.

Additionally, Maani et al. (2020) examine environmental impacts of recycling different PV technologies, including crystalline silicon and cadmium telluride modules. Their results show that recycling reduces environmental burdens but requires energy-efficient processing systems.

2.6 Research Gaps Identified

Despite extensive global research, several gaps remain:

1. Lack of PV-specific regulatory frameworks in developing countries.
2. Limited economic feasibility of advanced recycling technologies.
3. Insufficient integration of circular economy principles in national energy policies.
4. Weak reverse logistics infrastructure for PV waste collection.

These gaps are particularly relevant for Malaysia, where PV adoption is growing rapidly but waste management systems are still underdeveloped. The literature strongly suggests that failure to address these issues may result in long-term environmental and economic inefficiencies (Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145).

3. Methodology

3.1 Research Design

This study adopts a qualitative systematic review approach to evaluate sustainable photovoltaic (PV) waste management practices with a specific focus on Malaysia. The methodological framework is designed to synthesize existing academic literature, policy reports, and technical studies related to PV waste generation, recycling technologies, and circular economy integration. A structured interpretive synthesis method is employed to identify patterns, gaps, and emerging solutions in PV waste governance.

Unlike empirical studies that rely on field sampling, this review integrates secondary data from peer-reviewed journals and institutional reports to construct a conceptual framework for sustainable PV waste management. The approach is appropriate given the interdisciplinary nature of PV waste, which spans environmental science, materials engineering, and policy studies.

3.2 Data Collection Strategy

Data were collected exclusively from the provided references, ensuring strict adherence to the source limitation rule. The selected literature includes studies on PV recycling technologies (Azeumo et al., 2019), life cycle assessments (Badza et al., 2023), policy frameworks (Jain et al., 2022), and environmental impact analyses (Maani et al., 2020). Malaysian energy statistics and regulatory information were incorporated to contextualize findings within the national framework (DOE, 2022; Energy Commission, 2023).

The literature was categorized into five thematic domains:

1. PV waste generation and forecasting
2. Recycling technologies and material recovery
3. Environmental and life cycle impacts
4. Policy and governance frameworks
5. Circular economy applications

This thematic classification enables structured synthesis and comparative analysis across different studies.

3.3 Analytical Framework

The study employs a circular economy-based analytical framework to evaluate PV waste management efficiency. The framework integrates three core dimensions:

- Technical dimension: Recycling efficiency, material recovery rates, and technological readiness
- Environmental dimension: Emissions reduction, toxicity mitigation, and life cycle sustainability
- Policy dimension: Regulatory enforcement, extended producer responsibility (EPR), and institutional coordination

This multi-dimensional approach allows for a comprehensive assessment of PV waste systems beyond technical recycling performance.

3.4 PV Waste Flow and System Modeling

A conceptual PV waste flow model is developed to represent the lifecycle of photovoltaic modules in

Malaysia. The model includes:

- Installation and operational phase
- End-of-life decommissioning
- Collection and transportation systems
- Pre-processing (dismantling and sorting)
- Material recovery (mechanical and chemical recycling)
- Secondary material utilization

Studies indicate that efficient recovery systems can significantly reduce landfill dependency while enabling material circularity (Chowdhury et al., 2020). However, system inefficiencies often arise due to weak reverse logistics and lack of standardized collection infrastructure.

3.5 Evaluation Criteria

The sustainability of PV waste management systems is assessed using the following criteria:

- Material recovery efficiency (%)
- Environmental impact reduction potential
- Economic feasibility of recycling processes
- Policy alignment with national renewable energy goals
- Scalability within developing country contexts

These criteria allow for comparative evaluation of global best practices and their applicability to Malaysia.

3.6 Limitations of Methodology

The study is limited by its reliance on secondary data, which may not fully capture real-time operational challenges in Malaysia's PV waste sector. Additionally, variability in reporting standards across studies may introduce inconsistencies in comparative analysis. Despite these limitations, the structured synthesis approach provides a robust conceptual foundation for policy and research development.

4. Results / Findings

4.1 Emerging PV Waste Generation Trends

The analysis indicates a rapidly increasing trajectory of photovoltaic waste generation globally, driven by large-scale solar deployment. Studies show that early-generation PV installations are approaching end-of-life phases, creating a future surge in disposal volumes (Choi & Fthenakis, 2014). In developing contexts, including Malaysia, this trend is expected to intensify due to accelerated renewable energy adoption under national energy policies (Energy Commission, 2023).

A critical finding is that PV waste is not yet a dominant waste stream in Malaysia but is projected to become significant within the next two decades. This delay provides a strategic window for developing proactive waste management infrastructure.

4.2 Technological Recovery Potential

The findings highlight strong technical potential for PV material recovery through both mechanical and chemical processes. Azeumo et al. (2019) demonstrate that hybrid recycling approaches can efficiently separate glass, silicon, and metallic fractions. Similarly, Chowdhury et al. (2020) report that advanced recycling systems can recover up to 90% of module components under optimized conditions.

However, economic constraints remain a major barrier. High processing costs and lack of large-scale recycling facilities reduce commercial viability. This creates a gap between technical feasibility and real-world implementation.

4.3 Environmental Implications

Life cycle evidence indicates that PV systems provide significant environmental benefits during operational phases but generate end-of-life burdens if unmanaged. Badza et al. (2023) highlight that improper disposal increases lifecycle emissions and resource inefficiency. Maani et al. (2020) further confirm that recycling reduces environmental impacts compared to landfill disposal, particularly for crystalline silicon modules.

Despite these benefits, environmental gains are highly dependent on the efficiency of collection and processing systems. Weak infrastructure can significantly reduce sustainability outcomes.

4.4 Policy and Institutional Gaps

A key finding is the absence of a dedicated photovoltaic waste management policy in Malaysia. Existing e-waste regulations (DOE, 2022) do not fully address PV-specific material flows or extended producer responsibility mechanisms. This regulatory gap limits the development of structured recycling systems.

International studies indicate that countries with strong EPR frameworks achieve higher recycling rates and better resource recovery outcomes (Jain et al., 2022). Malaysia currently lacks similar enforcement mechanisms, leading to fragmented waste management practices.

4.5 Circular Economy Opportunities

The results suggest strong potential for integrating circular economy principles into PV waste management systems. Goh et al. (2024) demonstrate that recovered PV materials can be reused in construction applications,

supporting resource valorization and reducing dependency on virgin materials.

However, implementation remains limited due to lack of industrial integration and market development for secondary materials. Strengthening industrial symbiosis is therefore essential for achieving circularity.

4.6 Systemic Barriers in Malaysia

Key systemic barriers identified include:

- Lack of reverse logistics infrastructure
- Limited recycling technology adoption
- Absence of PV-specific regulations
- Low economic incentives for recyclers

These barriers collectively hinder the development of a sustainable PV waste management ecosystem.

5. Discussion

The findings of this review highlight a clear structural mismatch between the rapid expansion of photovoltaic (PV) deployment in Malaysia and the slow development of end-of-life (EoL) waste management systems. While solar energy is widely recognized as a low-carbon solution, the analysis confirms that its sustainability is highly dependent on how PV waste is managed after operational life. Without integrated recovery systems, the environmental benefits of solar energy risk being partially offset by downstream waste burdens.

A key theoretical implication emerging from the synthesis is the relevance of circular economy principles as a corrective framework for linear PV lifecycle systems. The literature consistently shows that PV modules contain recoverable high-value materials, yet these resources are often lost due to inadequate collection and processing systems (Chowdhury et al., 2020). From a systems perspective, this indicates inefficiency not at the technological level alone, but within institutional and logistical structures governing waste flow.

The comparison of global studies reveals that technological readiness for PV recycling is relatively advanced. Mechanical separation and chemical extraction methods are capable of recovering up to 90% of materials under optimized conditions (Azeumo et al., 2019). However, this technical capability does not translate into real-world sustainability without supportive economic and policy environments. For instance, high operational costs and lack of centralized recycling facilities reduce adoption rates, especially in developing economies. This aligns with broader observations that renewable energy waste streams are often underestimated in national planning frameworks (Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145).

From a Malaysian perspective, the findings suggest that existing e-waste governance structures are insufficient for PV-specific waste complexity. Although regulatory mechanisms under the Department of Environment provide general waste management guidelines, they do not address the unique material composition and reverse logistics requirements of solar panels (DOE, 2022). This regulatory gap creates fragmentation across collection, dismantling, and recycling stages, resulting in inefficient material recovery.

Another important insight is the role of life cycle assessment (LCA) in evaluating true environmental performance. Studies indicate that PV systems are highly beneficial during the operational phase but may generate significant environmental burdens at end-of-life if not properly managed (Badza et al., 2023). This introduces a critical trade-off: renewable energy expansion must be accompanied by parallel investment in waste infrastructure to ensure full lifecycle sustainability.

The discussion also highlights policy inertia as a major barrier. Countries with established extended producer responsibility (EPR) systems demonstrate more effective PV waste recovery outcomes, suggesting that regulatory design is a key determinant of sustainability performance (Jain et al., 2022). Malaysia's current absence of PV-specific EPR mechanisms limits accountability across the supply chain, reducing incentives for manufacturers to engage in recycling activities.

Circular economy applications present promising opportunities for Malaysia. The potential reuse of recovered PV materials in construction and industrial applications demonstrates that waste can be transformed into secondary resources (Goh et al., 2024). However, this requires coordinated industrial ecosystems, market demand for recycled materials, and technological standardization. Without these conditions, circularity remains conceptual rather than operational.

A notable contradiction identified in the literature is between environmental potential and economic feasibility. While recycling offers clear environmental benefits, its financial viability remains uncertain in low-scale systems (Maani et al., 2020). This tension suggests that policy intervention, subsidies, or producer responsibility schemes may be necessary to bridge the economic gap.

Overall, the synthesis indicates that Malaysia is at an early but critical stage in PV waste management

development. The next decade presents a strategic opportunity to establish integrated systems before waste volumes escalate significantly. Failure to act proactively may result in increased environmental burdens and missed resource recovery opportunities.

6. Conclusion

This review examined the sustainable management of photovoltaic waste in Malaysia through a comprehensive synthesis of global literature, technological developments, and policy frameworks. The study confirms that while photovoltaic systems offer substantial environmental benefits during operation, their end-of-life phase presents emerging sustainability challenges that must be addressed through structured waste management systems.

The analysis demonstrates that technological solutions for PV recycling are already available, including mechanical and chemical recovery processes capable of high material extraction efficiency (Azeumo et al., 2019). However, the absence of integrated policy frameworks and reverse logistics infrastructure in Malaysia limits their practical implementation. Existing e-waste regulations are insufficient to manage the complexity and scale of future PV waste streams (DOE, 2022).

A key contribution of this study is the identification of circular economy integration as a central strategy for sustainable PV waste management. By transforming discarded modules into secondary resources, Malaysia can reduce environmental impacts while enhancing resource efficiency (Goh et al., 2024). However, achieving this transition requires coordinated policy intervention, industrial collaboration, and technological investment.

The study also reinforces that renewable energy sustainability must be assessed across the full life cycle. Without end-of-life planning, the environmental advantages of solar energy may be partially undermined by waste accumulation and resource loss. This is consistent with broader global concerns regarding renewable energy waste governance (Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145).

Future research should focus on empirical assessment of PV waste generation in Malaysia, development of cost-effective recycling technologies, and evaluation of policy instruments such as extended producer responsibility (EPR). Strengthening these areas will be essential for ensuring that Malaysia's renewable energy transition remains environmentally and economically sustainable.

REFERENCES

1. Artaş, S. B., Kocaman, E., Bilgiç, H. H., Tutumlu, H., Yağlı, H., & Yumrutaş, R. (2023). Why PV panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation. Process Safety and Environmental Protection, 174, 63–78.
2. Azeumo, M. F., Germana, C., Ippolito, N. M., Franco, M., Luigi, P., & Settimio, S. (2019). Photovoltaic module recycling, a physical and a chemical recovery process. Solar Energy Materials and Solar Cells, 193, 314–319.
3. Badza, K., Soro, Y. M., & Sawadogo, M. (2023). Life cycle assessment of a 33.7 MW solar photovoltaic power plant in the context of a developing country. Sustainable Environment Research, 33(1), 38.
4. Bernama. (2022, May 17). RM48.34 juta kos tenaga berjaya dijimatkan tahun lepas. Astro.
5. Choi, J.-K., & Fthenakis, V. (2014). Crystalline silicon photovoltaic recycling planning: macro and micro perspectives. Journal of Cleaner Production, 66, 443–449.
6. Chowdhury, Md. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, Md., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews, 27, 100431.
7. Damo, U. M., Ahmed, T., Ozoegwu, C. G., Sambo, A., Aktas, A., Akca, H., Alam, M., & Bahaj, A. S. (2024). Solar PV potential in Africa for three generational time-scales: present, near future and far future. Solar Energy, 275, 112638.
8. DOE. (2022). E-waste Management in Malaysia. Department of Environment, Ministry of Environment and Water.
9. Dogra, R., Kumar, S., and Gupta, N. (2022). Application of Artificial Neural Network to Solar Potential Estimation in Hilly Region of India. Journal of Renewable Energy and Environment, 9(3), 10–16.
10. Energy Commission. (2023). Electricity Statistics - Renewable Energy Projects. Suruhanjaya Tenaga.
11. Gibson, M. & Demir, E. (2022). Electronic Waste (E-Waste) Management for Off-grid Solar Solutions in Displacement Settings.
12. Goh, K. C., Kurniawan, T. A., Goh, H. H., Zhang, D., Jiang, M., Dai, W., Khan, M. I., Othman, M. H. D., Aziz, F., Anouzla, A., & Meidiana, C. (2024).

Harvesting valuable elements from solar panels as alternative construction materials: A new approach of waste valorization and recycling in circular economy for building climate resilience. Sustainable Materials and Technologies, e01030.

13. Gönen, Ç., & Kaplanoğlu, E. (2019). Environmental and economic evaluation of solar panel wastes recycling. Waste Management & Research: The Journal for a Sustainable Circular Economy, 37(4), 412–418.

14. Gupta, N., Bhaskar, M. Sagar, Kumar, S., Almakhles, D. J., Panwar, T., Banyal, A., Sharma, A. and Nadda, A. (2024). Review on Classical and Emerging Maximum Power Point Tracking Algorithms for Solar Photovoltaic Systems. Journal of Renewable Energy and Environment, 11(2), 18–29.

15. Hebali, M., Ibari, B., Bennaoum, M., Beyour, M. E. A., Berka, M., Azzeddine, H. A., & Maachou, A. (2024). Electrical Properties of ITO/Al0.7Ga0.3As/ITO Solar Cell With and Without Defects. Journal of Renewable Energy and Environment, 11(2), 163–167.

16. Innovations and Trends in Solar Panel Recycling. (2024, January 19). Groundsailer Media.

17. Jain, S., Sharma, T., & Gupta, A. K. (2022). End-of-life management of solar PV waste in India: Situation analysis and proposed policy framework. Renewable and Sustainable Energy Reviews, 153, 111774.

18. Li, J., Shao, J., Yao, X., & Li, J. (2023). Life cycle analysis of the economic costs and environmental benefits of photovoltaic module waste recycling in China. Resources, Conservation and Recycling, 196, 107027.

19. Maani, T., Celik, I., Heben, M. J., Ellingson, R. J., & Apul, D. (2020). Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. Science of The Total Environment, 735, 138827.

20. Mahmoudi, S., Huda, N., & Behnia, M. (2021a). Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels. Resources, Conservation and Recycling, 164, 105145.