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SUSTAINABLE SOLAR: ADDRESSING THE GROWING NEED FOR PV PANEL RECYCLING

Tariq Umar[1], Sa'id Ahmed[2] and Muhammad Qasim Rana[3]

ABSTRACT

The rapid expansion of solar energy has raised critical concerns regarding the disposal of end-of-life photovoltaic (PV) panels. This research aims to assess the current landscape of solar panel recycling and explore the effectiveness of regulatory frameworks, recycling technologies, and policy interventions in supporting a sustainable solar energy future. Employing a mixed-methods approach, the study combines secondary data analysis of regulatory framework and policies from European Union, United Kingdom, United States and Asia with cross-national case studies of Germany, Japan, and the United Kingdom. The research evaluates recycling infrastructure, cost implications, material recovery rates, and public awareness to understand existing gaps and opportunities. Findings indicate that while recycling offers substantial environmental and economic benefits—such as resource conservation, job creation, and emissions reduction—barriers including high costs, limited facilities, and low consumer engagement impede widespread adoption. Emerging innovations in mechanical and chemical recycling processes show promise in improving material recovery rates and reducing energy input. The study also highlights how extended producer responsibility (EPR) schemes and circular economy policies can strengthen compliance and investment. Addressing these challenges is essential to reinforce solar energy's contribution to climate goals and to ensure that PV technology remains sustainable over its entire lifecycle. The study's implications call for coordinated global action, stronger regulatory enforcement, technological advancement, and public awareness to build an efficient and economically viable recycling ecosystem for solar panels.

Keywords: *Energy; Solar Energy; Renewable Energy; Solar Panel Recycling; Waste Management and Disposal.*

1. INTRODUCTION

The rapid expansion of solar power generation has led to a sharp rise in the number of installed photovoltaic (PV) panels worldwide (Wanner, 2019). While these panels are essential for achieving low-carbon energy goals, their eventual disposal presents a mounting environmental concern (Kaliyannan et al., 2025). At the end of their lifecycle, decommissioned panels may contribute to electronic waste if not managed properly, releasing hazardous materials such as lead and cadmium into the environment (Mitra &

[1] Senior Lecturer, School of Architecture and Environment, University of the West of England, UK, tariqumar1984@gmail.com
[2] Senior Lecturer, School of Built Environment and Geography, Kingson University, UK, sahmed@kingston.ac.uk
[3] Lecturer, University of the Built Environment, UK, mrana@ube.ac.uk

Maiti, 2021). In this context, solar panel recycling offers a crucial opportunity to recover valuable resources such as silicon, silver, and aluminium, reduce dependency on virgin materials, and minimise environmental degradation (Preet & Smith, 2024).

The United Kingdom, in alignment with global climate objectives, has actively promoted the deployment of solar energy systems (Gan et al., 2023). With over 13.5 GW of installed capacity, the UK is expected to experience a significant increase in end-of-life PV modules in the coming years (The Engineer, 2024). Regulatory mechanisms such as the Waste Electrical and Electronic Equipment (WEEE) Directive have been introduced to ensure that solar manufacturers and suppliers take responsibility for the disposal and recycling of PV panels (Majewski et al., 2021). Programmes like PV Cycle have emerged to support compliance and facilitate producer responsibility initiatives across the UK and Europe (Nain & Anctil, 2024).

Globally, other countries are also recognizing the need for comprehensive recycling solutions. Germany has incorporated PV waste into its broader electronic waste management policy frameworks (Sharma et al., 2019), while Japan has pioneered innovative chemical recycling processes for silicon extraction (Chen et al., 2024). In the United States, states such as California have established legislative frameworks to regulate PV disposal, alongside institutional efforts to improve recycling efficiency (Ali et al., 2023).

Despite these developments, a unified and scalable approach to solar panel recycling remains elusive (Badran & Lazarov, 2025). High costs, insufficient infrastructure, and limited public awareness persist as major barriers to widespread adoption (Lawal, 2024; Nain & Kumar, 2023). These challenges are particularly urgent as the volume of decommissioned solar panels is expected to surge globally in the next two decades.

The aim of this study is to examine the policy landscape, technological approaches, and implementation challenges of solar panel recycling, with a specific focus on the UK and comparative international contexts. This paper seeks to assess the current state of practice, identify critical gaps, and offer insights for shaping a more sustainable and circular end-of-life strategy for photovoltaic technologies.

2. RESEARCH METHOLODY

This study adopts a qualitative, multiple-case study design to examine solar panel recycling practices in the UK with a comparison with other selected countries. The aim is to assess waste management strategies, regulatory frameworks, and industry-led initiatives associated with photovoltaic (PV) panel recycling. Countries selected for case study analysis include Germany, and the UK, with a comparison with regulatory framework in EU, United States and Aisa – mainly Japan. These were chosen based on three criteria: (1) the presence of well-established PV recycling programmes, (2) compliance with extended producer responsibility (EPR) policies, and (3) the scale of solar panel deployment and waste generation. The selection reflects variation in regulatory maturity and implementation effectiveness across contexts.

The research integrates secondary data analysis with case study evaluations to provide a holistic understanding of the topic (Guetterman & Fetters, 2018). Data sources include government reports, academic publications, and industry white papers (Calantone & Vickery, 2010). Key documents analysed comprise the Waste Electrical and Electronic Equipment (WEEE) Directive, International Energy Agency (IEA) reports, and PV Cycle publications, which offer insights into regulatory structures and technological advancements (Bowen, 2009). Data from policy institutions and market research firms were also reviewed to estimate the growth of PV installations and forecast waste management requirements.

The analytical approach is primarily qualitative. Thematic analysis was applied to case study materials to identify recurring patterns and major themes (Clarke & Braun, 2017). These themes included policy effectiveness, technological barriers, and industry collaboration. A coding framework was developed to systematically organise and interpret the data (Brown et al., 2003). Although the original research design referenced mixed-methods (Foroudi & Foroudi, 2024), the study ultimately did not incorporate primary quantitative analysis due to inconsistent availability of reliable numeric data across the selected countries. As such, references to quantitative content are limited to descriptive statistics available within secondary sources.

Case study analysis, guided by Stake (2013) methodology, was employed to explore real-world applications of PV recycling. The countries included offered diverse yet comparable regulatory and technical experiences, which allowed for identification of best practices and barriers that may inform policy transfer or improvement.

The research adhered to ethical guidelines by ensuring proper citation of all secondary data sources to acknowledge intellectual property rights (Patel et al., 2016). Efforts were made to present an unbiased analysis by including diverse perspectives from multiple sources (Loscalzo & Giannini, 2025). Data triangulation was used to reduce bias and enhance reliability. Limitations include variation in data availability and possible biases within source materials.

3. THE IMPORTANCE AND IMPACT OF SOLAR PANEL RECYCLING

The global shift towards renewable energy has accelerated solar panel installations, with projections indicating that millions of tons of photovoltaic (PV) waste will be generated by 2050 (Tawalbeh et al., 2021). Without adequate recycling, this growing volume of waste threatens to overwhelm landfills, resulting in environmental degradation and resource loss (Abdolmaleki et al., 2025). Solar panel recycling offers far-reaching benefits across environmental, economic, and social dimensions, supporting global sustainability goals and the circular economy (Srivastava et al., 2025). To structure these benefits, Table 1 presents a summary of key thematic insights regarding the importance of PV panel recycling.

Table 1: Key aspects of solar panel recycling and their impacts

Theme	Summary	Key references
Resource Recovery	Recovers valuable materials like silicon, silver, and aluminium, reducing raw material extraction and pollution.	(Gajare et al., 2025; Preet & Smith, 2024; Al-Alimi et al., 2024)
Environmental Protection	Prevents hazardous substances (e.g. lead, cadmium) from contaminating ecosystems; supports circular economy.	(Nain & Kumar, 2022; Siddiqua et al., 2022; Rabaia et al., 2022)

Theme	Summary	Key references
Economic and Job Creation	Drives green innovation, creates new industries and employment in waste management and material recovery.	(Dias et al., 2022; Sarkhoshkalat et al., 2024; Collis et al., 2023)
Reduced Energy Demand	Significantly lowers energy use in panel manufacturing by reusing materials such as silicon wafers.	(Fernández-González, 2025; Bulińska et al., 2025; Maghraby et al., 2025)
Alignment with SDGs	Contributes to SDG 12 (Responsible Consumption) and SDG 13 (Climate Action) through reduced emissions and sustainable production.	(Gan et al., 2023; Arora & Mishra, 2023; Oduro et al., 2024)
Need for Infrastructure	Highlights the urgent requirement for robust recycling infrastructure and policy enforcement globally.	(Morone et al., 2025; Altassan, 2023; Adebisi et al., 2023)

Following this overview, it is evident that solar panel recycling is a cornerstone of sustainable solar deployment. The recovery of high-value materials like silicon and aluminium not only reduces the environmental costs of mining but also promotes resource efficiency (Preet & Smith, 2024; Al-Alimi et al., 2024). Additionally, the containment of toxic materials like cadmium and lead addresses crucial public health and land contamination risks (Nain & Kumar, 2022; Siddiqua et al., 2022).

Economically, solar recycling introduces job creation and innovation opportunities, particularly where regulatory support incentivises circular supply chains (Dias et al., 2022; Sarkhoshkalat et al., 2024). Energy savings from reusing processed materials, such as silicon, further enhance the lifecycle efficiency of solar technology (Bulińska et al., 2025; Maghraby et al., 2025). Furthermore, recycling aligns directly with the United Nations' Sustainable Development Goals, making it a necessary pillar for environmentally responsible policy agendas (Gan et al., 2023; Arora & Mishra, 2023).

Yet, these benefits remain largely unrealised in many parts of the world due to gaps in infrastructure, regulation, and public awareness. Although countries like Germany and France have established dedicated PV recycling plants, other regions face logistical and financial challenges that hinder scale-up (Morone et al., 2025; Altassan, 2023). Bridging these gaps will require coordinated efforts from governments, industries, and civil society to expand infrastructure, implement policy incentives, and increase consumer awareness (Daniela-Abigail et al., 2022; Adebisi et al., 2023).

4. REGULATORY FRAMEWORK AND POLICIES

4.1 EUROPEAN UNION REGULATIONS

The European Union (EU) has been at the forefront of solar panel recycling policies, primarily through the Waste Electrical and Electronic Equipment (WEEE) Directive (Lesniewska, 2017). This directive classifies solar panels as e-waste, making manufacturers responsible for their collection and recycling at end-of-life. The Extended Producer Responsibility (EPR) model mandates that producers finance the proper disposal and recycling of solar panels, ensuring that recycling programs are sustainable and widely accessible (Khawaja et al., 2021). PV Cycle, an industry-led compliance scheme, has been instrumental in facilitating the collection and recycling of solar panels across EU member states (Gerold & Antrekowitsch,2024).

4.2 UNITED KINGDOM POLICIES

Following Brexit, the UK has retained the core principles of the WEEE Directive while making adjustments to fit national policies (Cole et al., 2019). The UK Environment Agency enforces solar panel recycling regulations, requiring manufacturers and importers to register and contribute to end-of-life management schemes (Nidhi et al., 2024). Companies failing to comply face penalties, ensuring accountability. Additionally, the UK's Circular Economy Strategy emphasizes the need for improved solar panel recycling infrastructure and incentives for developing efficient material recovery technologies (Gregson et al., 2015).

4.3 UNITED STATES REGULATIONS

Solar panel recycling regulations in the United States vary by state (Curtis et al., 2021). California, a leader in solar energy, has implemented strict regulations under the California Department of Toxic Substances Control (DTSC), classifying solar panels as universal waste and requiring responsible recycling (Heath et al., 2022). Other states, such as Washington and New York, have introduced similar policies, but federal legislation remains limited (Tabassum et al., 2021). The Solar Energy Industries Association (SEIA) has launched voluntary recycling initiatives, encouraging manufacturers to participate in panel take-back and recycling programmes (Komoto et al., 2018).

4.4 POLICIES IN ASIA

In Asian, Japan has pioneered advanced solar panel recycling methods, supported by the Ministry of the Environment and the Ministry of Economy, Trade, and Industry (METI) (Goh et al., 2024). The country has developed innovative chemical recycling techniques to extract high-purity silicon from PV panels. China, the world's largest producer of solar panels, is working on implementing a national recycling framework, driven by environmental concerns and the need for sustainable resource management. Government-backed initiatives encourage research and development in recycling technologies, aiming to establish large-scale solar panel recycling plants (Song & Feng, 2024).

4.5 FUTURE POLICY DIRECTIONS

As the global volume of decommissioned solar panels continues to rise, there is a growing need for standardized international regulations (Mahmoudi et al., 2021). Key recommendations arriving from Lunardi et al. (2018) and Abila and Kantola (2019) include: (i) Strengthening EPR mandates to ensure global manufacturers contribute to recycling efforts, (ii) Establishing international guidelines for solar panel disposal and recycling efficiency benchmarks, (iii) Providing financial incentives for companies investing in innovative recycling technologies.

By harmonizing global policies and expanding regulatory frameworks, governments can create a more sustainable future for solar energy, ensuring that the industry remains environmentally responsible in the long term.

5. COMPARATIVE EFFECTIVENESS OF REGULATORY APPROACHES: A CASE STUDY PERSPECTIVE

5.1 GERMANY: SYSTEMATIC IMPLEMENTATION AND POLICY-DRIVEN SUCCESS

Germany demonstrates a highly structured and centralised recycling model. Under the ElektroG law, aligned with the WEEE Directive, PV modules have been categorised as e-waste since 2015, placing financial responsibility for collection and recycling on producers (Electrical and Electronic Equipment Act., 2005). The PV Cycle scheme operates over 300 collection points nationally. Germany's recycling infrastructure is comprehensive, supported by national policy enforcement and technical R&D investments from the Federal Environment Agency (Andersen, 2024). The country achieves collection rates above 85%, with material recovery efficiencies of 80–90% for glass and aluminium, and 60–70% for silicon. Recycling costs range from \$270 to \$325 per ton, partially offset by material resale and regulatory subsidies (Held & Wessendorf, 2024). Environmental benefits include avoidance of 400,000 tonnes of CO_2-equivalent emissions annually (Germany Trade & Investment, 2024). Closed-loop recycling systems are integrated with e-waste infrastructure, enhancing scalability (Sarkhoshkalat et al., 2024). This model reflects a high-performing system with well-aligned regulatory and operational mechanisms.

5.2 JAPAN: INNOVATION-LED, TECHNOLOGY-INTENSIVE RECYCLING

Japan's regulatory strategy prioritises R&D and technological precision, backed by the Ministry of Environment and METI (Herrador et al., 2022). The policy focus is on innovation-led efficiency through chemical separation and modular eco-design (Sakao et al., 2024). Japan achieves PV recycling rates of 65–70%, varying by prefecture (Komoto et al., 2022). Advanced hydrometallurgical and thermal techniques allow recovery of up to 95% of silicon and 80% of silver, exceeding global benchmarks (Theocharis et al., 2022). Costs range from \$230 to \$300 per ton—lower than Germany's—due to improved yield from sophisticated processes (Cheng et al., 2022). Environmental indicators show a 32% reduction in toxic leachate incidents near legacy solar sites (Moshkal et al., 2024). Initial investments are significant, with state-supported pilot projects driving innovation. While effective in high-density regions, the model's scalability hinges on continued public investment and national coordination.

5.3 UNITED KINGDOM: REGULATORY CONTINUITY AMIDST IMPLEMENTATION GAPS

Post-Brexit, the UK has retained WEEE-aligned principles but lacks PV-specific enforcement measures. Only an estimated 35–45% of decommissioned panels are recycled through certified channels; the rest enter general waste streams (Czajkowski et al., 2022). The country operates just three dedicated PV recycling facilities, limiting geographic coverage and accessibility (Ganpatsinh et al., 2024). Recycling costs range between \$225 and \$275 per ton—higher than landfill disposal—creating economic disincentives (Ganpatsinh et al., 2024). While the Circular Economy Strategy supports responsible waste practices, it lacks binding targets specific to solar recycling (Sundar et al., 2023). Potential environmental risks from unmanaged waste include heavy metal leaching. However, recycling is estimated to reduce lifecycle carbon emissions by 65%

per module. Public–private partnerships have emerged, but most are in early stages and lack national coordination.

5.4 CROSS-CASE INSIGHTS AND POLICY IMPLICATIONS

The comparative analysis reveals significant regulatory divergences. Germany's model is policy-driven, enforceable, and integrated with national e-waste infrastructure, enabling high performance. Japan's model prioritises high-tech innovation and eco-design, yielding superior material recovery but with high initial investment and scalability challenges. The UK, while maintaining regulatory continuity, suffers from weak enforcement, fragmented infrastructure, and limited uptake.

Regulatory Alignment and Divergence: All three countries align with EPR principles, but only Germany enforces producer compliance rigorously. Japan leverages R&D policy, while the UK lacks binding PV-specific targets. The presence or absence of enforceable regulations appears to be a key determinant of implementation success.

Outcomes and Metrics: Germany leads in collection and recovery rates, while Japan surpasses in technical efficiency. The UK lags across most performance indicators. Recycling rates relative to estimated end-of-life product volumes are highest in Germany (~85%), followed by Japan (~65%), and lowest in the UK (~40%).

Infrastructure and Investment: Germany and Japan have robust infrastructure networks, supported by public funding. Japan's initial investments in chemical recycling technologies offer long-term returns via material purity and energy savings. The UK's limited facilities constrain scale and efficiency.

Environmental and Economic Impact: All three countries demonstrate positive environmental outcomes, with PV recycling reducing carbon emissions and landfill pressure. However, cost recovery is strongest in Germany, where resale of materials and regulatory subsidies help offset processing expenses. Japan's advanced recovery efficiencies justify its upfront costs, while the UK struggles due to low economies of scale and weak policy support.

This comparative framework highlights that successful solar panel recycling depends on a combination of regulatory enforcement, infrastructure investment, technological capability, and cost-recovery strategies. Policymakers seeking to scale PV recycling must consider a hybrid model that integrates Germany's policy coordination with Japan's innovation and addresses the UK's implementation challenges. These case studies offer a practical roadmap for embedding circular economy principles in solar energy transitions worldwide.

6. OVERCOMING CHALLENGES AND ADVANCING SOLAR PANEL RECYCLING

To assess the real-world impact of solar panel recycling initiatives, this study evaluated case studies from Germany, Japan, and the United Kingdom. These countries were selected based on the presence of mature regulatory frameworks, national solar deployment scale, and differing approaches to recycling infrastructure and policy enforcement.

6.1 KEY CHALLENGES IN SOLAR PANEL RECYCLING

Despite the growing recognition of solar panel recycling, several obstacles hinder its widespread adoption (Salim et al., 2019). One major challenge is the high cost of recycling. The process of separating materials from decommissioned panels is complex and requires specialized technology, making it more expensive than landfill disposal (Krauklis et al., 2021). In addition, the lack of dedicated recycling infrastructure in many countries limits the accessibility of recycling programmes, particularly in regions with high solar energy adoption but insufficient waste management facilities (Kinally et al., 2022).

Another critical challenge is the low public awareness and participation in solar panel recycling programmes. Many solar panel owners, including residential and commercial users, are unaware of available recycling options, leading to improper disposal (Okoroigwe et al., 2020). Additionally, the varying composition of solar panels—with different materials and designs—adds to the complexity of recycling, requiring customized recycling techniques for different types of PV modules (Chowdhury et al., 2020).

6.2 INNOVATIONS AND FUTURE PROSPECTS

To overcome these challenges, technological advancements are being developed to improve recycling efficiency and cost-effectiveness (Kamboj & Ray, 2025). New chemical and mechanical recycling techniques allow for higher recovery rates of materials such as silicon and silver, making the process more economically viable (Theocharis et al., 2022). Researchers are also exploring design improvements, such as modular and easily disassemble solar panels, to facilitate recycling at the end of their lifecycle (Su et al., 2024).

Furthermore, government incentives and industry collaborations are essential to promoting solar panel recycling (Acharya et al., 2024). Policymakers can introduce financial incentives, such as tax credits and subsidies, to encourage manufacturers to adopt recycling-friendly designs and invest in advanced recycling facilities (Haksevenler et al., 2023). Public-private partnerships can also help scale up recycling programs, fostering innovation and expanding infrastructure.

In the long term, the development of a global standard for solar panel recycling could ensure consistent regulations and guidelines across different countries. International cooperation in research and policymaking will be vital in addressing the increasing volume of PV waste and establishing sustainable solutions for the solar energy industry.

By addressing these challenges through innovation, policy support, and industry engagement, solar panel recycling can become a key pillar in the transition to a truly circular and sustainable renewable energy system.

7. CONCLUSION

Solar panel recycling is an essential component of the sustainable energy transition. While solar energy offers a cleaner alternative to fossil fuels, the growing accumulation of end-of-life PV modules presents significant environmental and economic challenges. Without appropriate recycling measures, these panels could contribute to electronic waste, exacerbating landfill overflow and environmental degradation. However, by implementing effective recycling strategies, the renewable energy sector can achieve a truly circular economy that reduces waste, conserves valuable resources, and minimizes environmental harm. The current state of solar panel recycling presents both challenges and opportunities. While high costs, limited infrastructure, and lack of public awareness remain key barriers, advancements in recycling technology, policy support, and industry collaboration are paving the way for a more efficient and scalable recycling system. Countries such as Germany, Japan, and the United States are demonstrating successful models for PV recycling, proving that investment in recycling infrastructure can lead to significant long-term benefits. To enhance solar panel recycling efforts, a multi-faceted approach is required. Governments must implement stronger policies that mandate recycling and incentivize sustainable design. The private sector should continue investing in innovative recycling techniques that increase material recovery rates and reduce processing costs. Furthermore, raising public awareness about the importance of solar panel recycling will encourage responsible disposal practices and greater participation in recycling programs. Looking ahead, international cooperation will be crucial in standardizing recycling practices and ensuring a consistent, global approach to managing solar panel waste. Establishing a unified framework for recycling guidelines, best practices, and research collaboration can drive efficiency and scalability across different regions. By integrating sustainability into every stage of the solar panel lifecycle—from design to disposal—the renewable energy sector can fulfil its promise of delivering a cleaner, greener future. In conclusion, solar panel recycling is not merely a necessity but an opportunity to enhance the sustainability of the renewable energy industry. With continued technological advancements, policy improvements, and public engagement, solar panel recycling can evolve into a well-established, economically viable industry that supports both environmental protection and circular economy principles. The time to act is now—to ensure that solar energy remains a truly sustainable solution for generations to come.

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