Challenges and Potential Solutions for Managing Solar Module Waste in Developing Nations

Spring 2024 Master's Project

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1. Executive Summary

Although solar modules support a necessary global energy transition, the sunny technology is not without a dark side. A solar module, also known as a solar panel, is composed of an assembly of solar cells that convert energy from the sun into electricity. Solar modules have defined lifetimes, after which they become sources of hazardous waste. Considering an average module lifetime of 30 years, the International Renewable Energy Agency (IRENA) projects the global cumulative volume of solar module waste to reach 1.7 million metric tons by 2030 and 60 million metric tons by 2050.

Clearly, the projected surge in solar waste necessitates policies and strategies for management. Yet almost no international or national bodies have implemented solar waste-specific initiatives. Accordingly, this Master's Project asked: What are the challenges and potential solutions for managing solar module waste in developing nations? Developing nations, which are defined as sovereign states with a lower level of social and economic development, are experiencing an influx of solar installations. Despite this, relatively little research has examined the unique barriers developing nations will face in managing high volumes of solar waste.

This Master's Project aims to contribute to a broader understanding of the challenges hindering developing nations from implementing policies and practices for solar waste management. It also seeks to highlight research-based solutions that can tackle challenges. In order to identify both overarching challenges and potential solutions, this Master's Project employed a qualitative systematic review of relevant publications. Over 100 publications were screened against an inclusion and exclusion criteria, and ultimately 35 publications passed through the final quality assurance check and were coded according to core themes. These 35 publications were either reviews (9), modelled simulations (15), case studies (6), or cost-benefit analyses (5).

The final set of 35 publications revealed three key challenges to solar waste management in developing nations. First, there are few or no economic incentives to promote investment in solar waste management. Second, there is few or no coordination among solar panel producers and recyclers. Third, are no regulations, which then impedes a streamlined process for collection, transportation, and recycling.

In order to overcome these challenges, developing nations can introduce regulations and policies promoting extended producer responsibility, which would hold solar panel producers financially liable for collection and recycling. Developing nations may also implement a take-back or collection scheme for returning decommissioned panels. Investment in research and development is also recommended to investigate new frameworks and technologies for solar module recycling.

2. Background

2.1 Global Solar Module Waste Projections

A worldwide transition away from fossil-fuels to renewable energy sources is essential to limiting the global temperature rise to 1.5 °Celsius above pre-industrial levels and averting the worst impacts of global warming. According to IRENA, electricity generation will need to triple by 2050 in order to stay below this threshold, with 91% of the supply coming from solar and wind power. Solar supply has grown the fastest among renewable sources, with a twenty-six-fold increase from 2010 to 2022 (IRENA, 2023). Solar panel installations in particular have exploded, reaching an annual growth rate of 50% (Cheema et al., 2024).

While growth in global solar installations delivers many climactic benefits, this sunny technology is not without a dark side. Solar modules have a useful life of 20 to 30 years, after which they become hazardous electronic waste. In 2014, global annual electronic and electrical waste streams reached a record of 41.8 million metric tons, with solar modules accounting for 250,000 metric tons or 0.6%. This percentage will significantly rise in the coming years (IRENA, 2016).

Depending on whether solar modules reach or fail before their 30-year lifespan, IRENA projects solar module waste to account for between 1.7 and 8 million metric tons by 2030. Total solar module waste volume is projected to rise to between 60 and 78 million metric tons by 2050. The global ratio of solar waste to total solar generation capacity will reach between 4 and 14% by 2030 and rise over 80% by 2050 (IRENA, 2016).

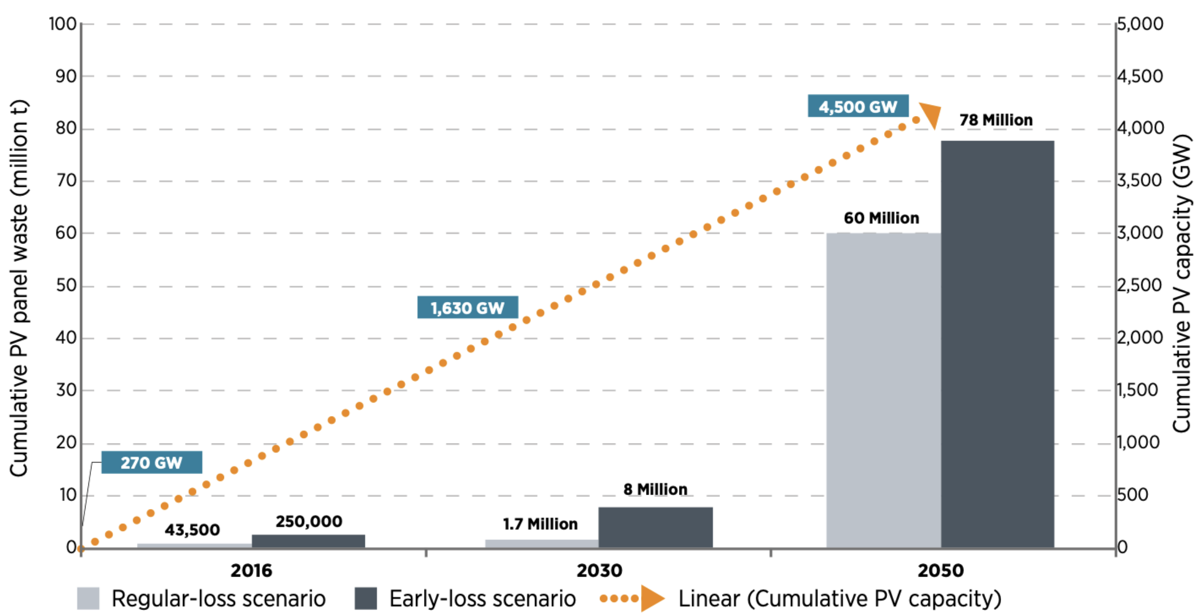

Figure 1: Global solar module waste projections based on a regular-loss scenario (modules reach 30-year lifetime and an early-loss scenario (modules deteriorate within 30 years) from 2016 to 2050 (IRENA, 2016).

At the end of 2050, China is projected to have accumulated the majority of solar module waste, generating between 13.5 and 20 million metric tons. The United States is forecast to have the second-most solar waste, followed by Japan, India, and Germany (IRENA, 2016). However, with an influx of solar installations in Latin America, Africa, and Southeast Asia, many more developing nations will also see considerable solar waste generation.

By 2050, Mexico, for example, is forecast to have accumulated 690,907 metric tons of solar module waste (Dominguez and Geyer, 2017). Brazil, which has one of the highest solar growth rates in the world, is expected to be a regional leader in waste, accumulating 300,000 metric tons by 2050. Indonesia and Malaysia, tropical countries with significant solar potential, are forecast to accumulate 600,000 and 190,000 metric tons, respectively, by 2050 (IRENA, 2016).

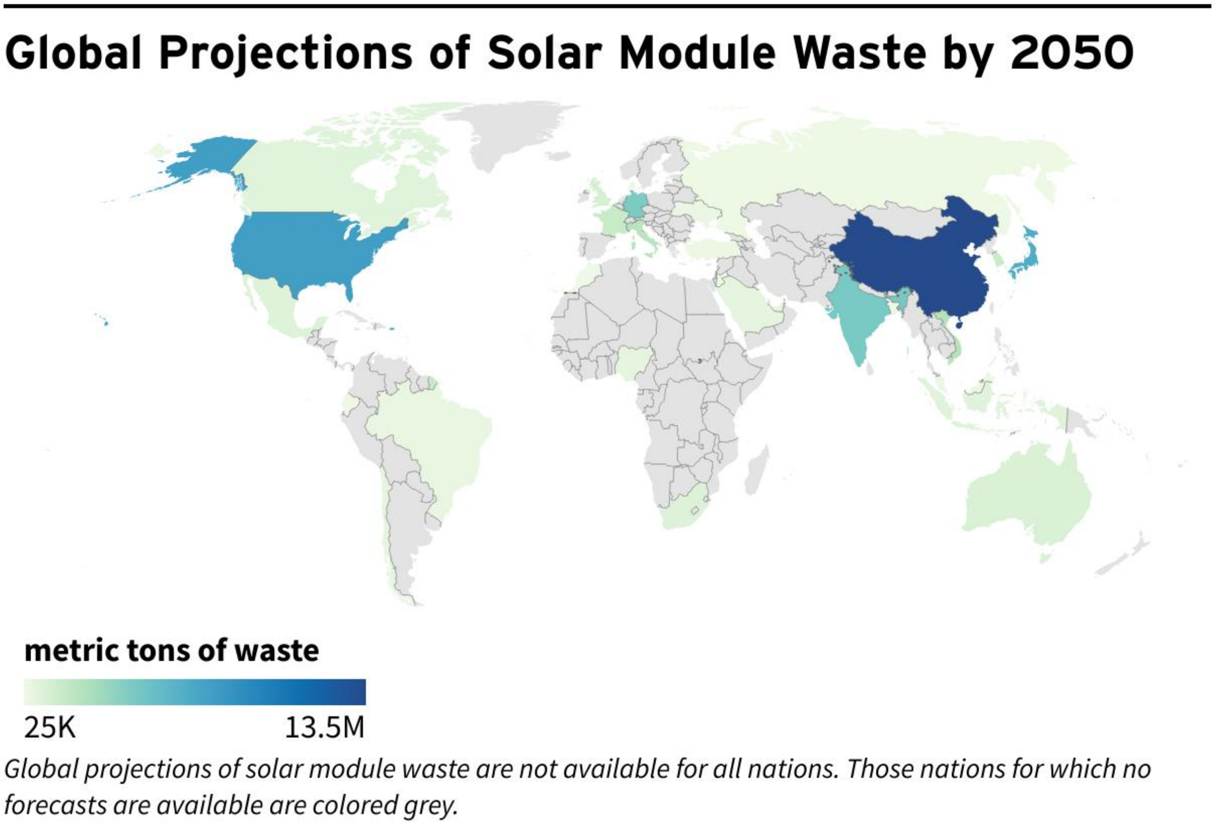

Figure 2: Solar module waste forecast by country based on a regular-loss scenario where modules reach their 30-year lifetime (Al-Zoubi et al., 2022; Dominguez and Geyer, 2017; IRENA, 2016; Tasnim et al., 2022).

2.2 Environmental Impacts of Solar Module Waste

Solar panels contain an array of toxic substances, including lead, cadmium, chromium, and antimony. Landfilling solar panels results in lead and cadmium leaching into the surrounding soil and groundwater. Once in soil or water, lead and cadmium can spread beyond the dumping area, with adverse consequences for the environment and human health (Sharma et al., 2024).

Leaching of lead, for example, can result in loss of biodiversity and impaired growth and reproductive function among flora and fauna. Lead exposure is also known to adversely impact human health. It is linked to kidney and nervous system damage and impaired brain development among children (Sharma et al., 2024).

Another toxic substance contained in solar modules, cadmium, is carcinogenic and increases the risk of lung, prostate, and renal cancer (Sharma et al., 2024). Scientific research has demonstrated that rainwater can wash cadmium from fragmented solar modules over a period of several months, increasing the risk of leaching (Ramos-Ruiz, et al., 2017). This will be of increasing concern as global warming results in more frequent and extreme weather events, including tornados and hurricanes.

In a single solar module, heavy metals account for less than 1% by weight (Xu et al., 2018). The weight of heavy metals accumulates quickly when reflecting on the scale of cumulative solar capacity. In 1.7 million solar panels, the amount forecast to become waste by 2030, there are approximately 100,000 pounds of cadmium (Shellenberger, 2022).

2.3 Global Approaches to Solar Waste Management

Given both the anticipated volume of solar module waste and its potential harms, global policies are essential to ensuring proper management. Yet, at present, the European Union (EU) is the only governing body that has adopted solar-specific waste regulations. In 2012, the EU officially revised its Waste Electrical and Electronic Equipment (WEEE) directive to include solar panels (Xu et al., 2018).

The WEEE directive establishes collection and recycling targets, sets minimum treatment requirements, and holds producers of solar modules legally liable for fulfilling certain requirements. First, producers are liable for financing public collection points and first-level treatment facilities. Second, producers are responsible for gathering information and reporting on the number of solar modules sold, collected, and forwarded for treatment. Lastly, producers are required to inform waste treatment facilities on how to properly store, dismantle, and recycle modules (IRENA, 2016).

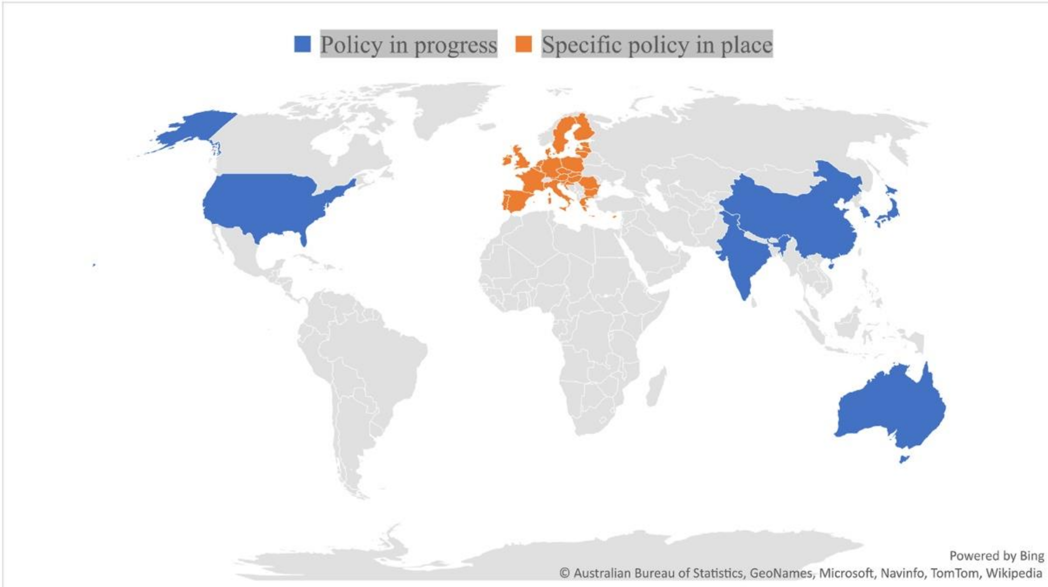

Figure 3: Status of available policies for management of solar modular waste (Ganesan and Valderrama, 2022).

In the United States, there are no solar-specific national waste laws. However, solar modules must be disposed of in accordance with the Resource Conservation and Recovery Act (RCRA), the regulatory framework for management of hazardous and solar waste. The RCRA requires discarded solar panels be tested to determine if the contained heavy metals exceed regulatory limits (IRENA, 2016).

Like the United States, China and India, which have among the most installed solar capacity, have no solar-specific waste regulations (IRENA, 2016). Instead, both nations regulate discarded modules under general waste laws. China's National Solid Waste Law governs the management of solid and hazardous waste and provides guidelines for collection and disposal (Ali et al., 2023). Research and development into solar waste recycling technologies has been sponsored by China's National High-tech R&D Programme (IRENA, 2016).

Under India's Hazardous Waste Rules, disposal of solar waste must include testing for toxicity. Industrial-scale electronic recycling infrastructure, while present in India, is not currently equipped to manage solar waste (IRENA, 2016).

3. Methodology

This Master's Project employed a qualitative systematic review to identify challenges and potential solutions for management of solar waste in developing nations. A qualitative systematic review is a "method for integrating or comparing the results from qualitative studies. It looks for 'themes' or 'constructs' that lie in or across individual studies" (Grant and Booth, 2009). This approach was selected because it is comprehensive in condensing and articulating a large body of research.

The first step in a qualitative systematic review is identifying relevant literature using keywords. The following Boolean strings were entered into Scopus and ScienceDirect:

a. ("solar panel" OR "photovoltaic panel") AND ("recycle" OR "end-of-life") AND ("low-middle" OR "emerging" OR "developing")

b. ("solar panel" OR "photovoltaic panel") AND ("recycle" OR "recycling" OR "end-of-life") AND ("Middle East" OR "Asia" OR "Africa" OR "Latin America")

The search was further limited to articles published in English between 2010 and 2024. The Scopus database found 42 documents relevant to the first Boolean string and one document relevant to the second. ScienceDirect found 66 documents relevant to the first Boolean string and 4 relevant to the second. An additional 20 documents were found entering the same search parameters into Google Scholar, for a total of 133 documents.

After the literature was collected, duplicate results were removed for a total of 107 documents. Then, the texts were screened for inclusion in this Master's Project based on the following criteria:

Inclusion criteria	The document described the status of solar waste management policies and practices; challenges hindering solar waste management; or potential solutions to facilitate solar waste management.
	The document focused on one or more developing nations.
	The document was publicly available or accessible via Duke University Libraries.
Exclusion criteria	The document was not related to solar waste management.
	The document did not specify a country or countries of study or was focused on a high-income nation.
	The document was not publicly available, not accessible via Duke University Libraries, or published in a language other than English.

Table 1: Inclusion and exclusion criteria for literature screening.

To screen the documents, a four-phase approach described in Salim et al., 2019 was adopted. First, if the title of the document was sufficient, it was deemed eligible for inclusion. Otherwise, the keywords needed to be examined. If neither the title nor the keywords were relevant to the research question, then the abstract and full-text were sequentially reviewed.

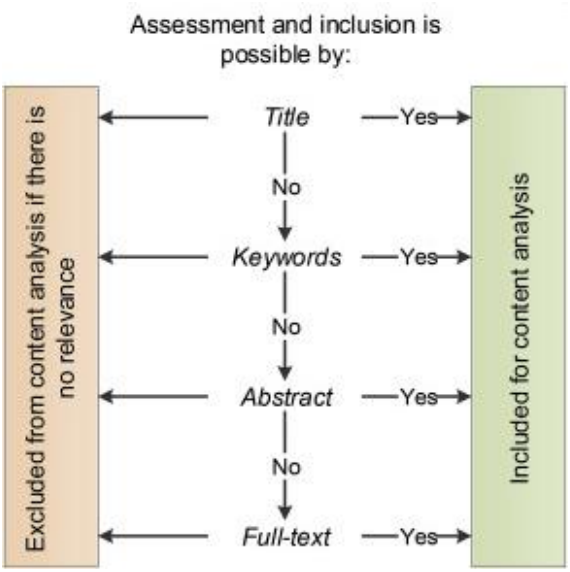

Figure 4: Framework for screening literature and determining eligibility (Salim et al., 2019).

During screening, 67 documents were deemed ineligible for inclusion based on either a lack of relevance or inaccessibility. The remaining 40 for were assessed for quality, appropriateness, and bias. A framework for deciphering each of the three characteristics was adopted from Girardeau et al., 2021 and modified:

Ways of Reporting	
Were the aim and objective of the study clearly stated?	Yes/Partly/No
Was there an adequate description of the methodology?	Yes/Partly/No
Are limitations in the study acknowledged and described?	Yes/Partly/No
Bias	
Are conclusions made well-grounded in the data and analysis?	Yes/Partly/No
Appropriateness	

Does the study place the findings of the context of interest?	Yes/Partly/No
Does the study suggest if and how the findings might be transferable to other settings?	Yes/Partly/No

Table 2: Quality assessment for determining inclusion.

During quality assessment, 5 papers were excluded for lacking thorough reporting. The remaining 35 papers were included in this Master's Project. The content of these 35 publications was first synthesized via open coding. This refers to the identification and categorization of challenges and potential solutions. Then, the publications were selectively coded. Core concepts were highlighted based on multiple publications reflecting that respective idea (Salim et al., 2019).

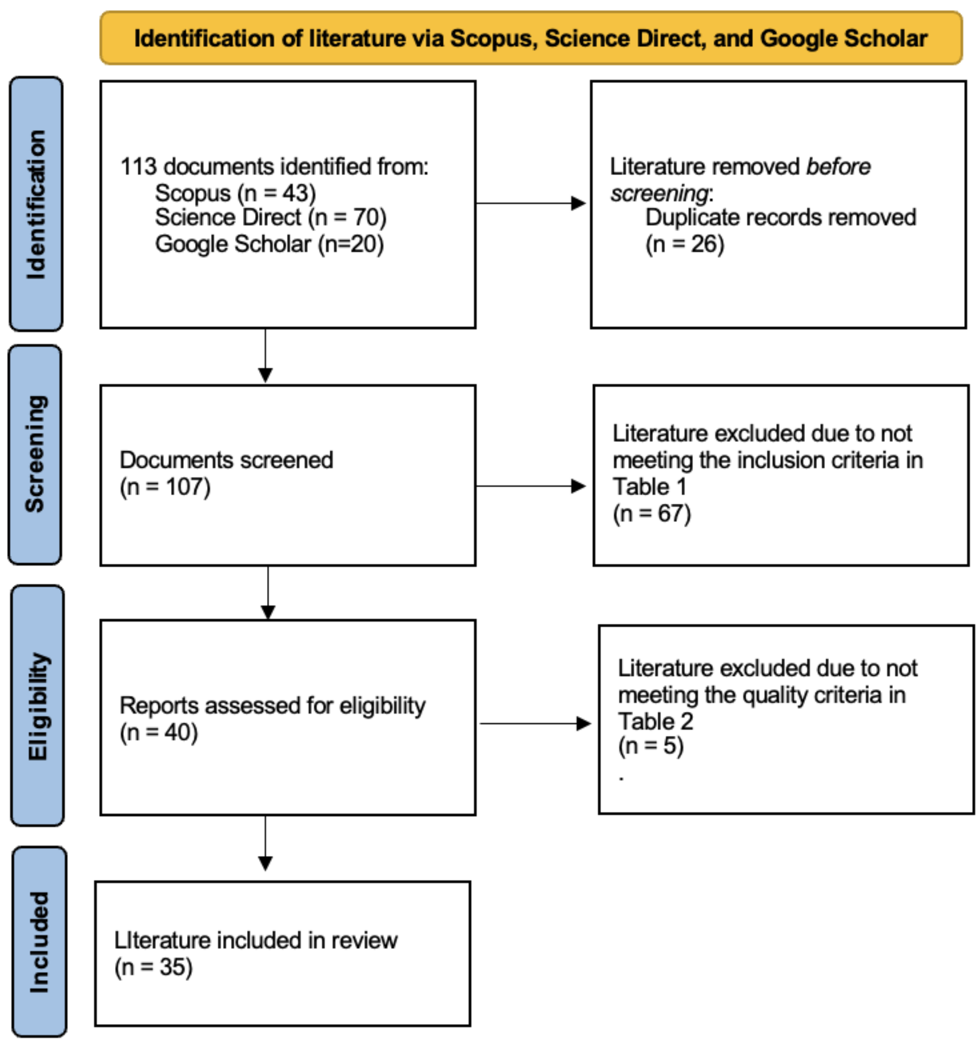

Figure 5: PRISMA diagram showing methodology overview.

4. Review Findings

4.1 Geographic Distribution of Literature

The 35 publications included in this research centered on 15 developing nations across North America, South America, Asia, Africa, and Europe. China is the most-studied nation; it is the geographic focus of 12 articles published between 2019 and 2024. India follows China and is the geographic focus of eight articles published between 2021 and 2023. Other countries with more than one included publication are Bangladesh and Vietnam.

Collectively, Asia is the most researched content and is represented in 83% of the included publications. This is likely because China and India are forecast to have among the most installed solar capacity and cumulative solar module waste. Conversely, there is scant and dispersed research regarding developing nations in Latin America and Africa. Accordingly, the academic understanding of challenges and potential solutions for managing solar waste in those regions is neither comprehensive nor well-substantiated.

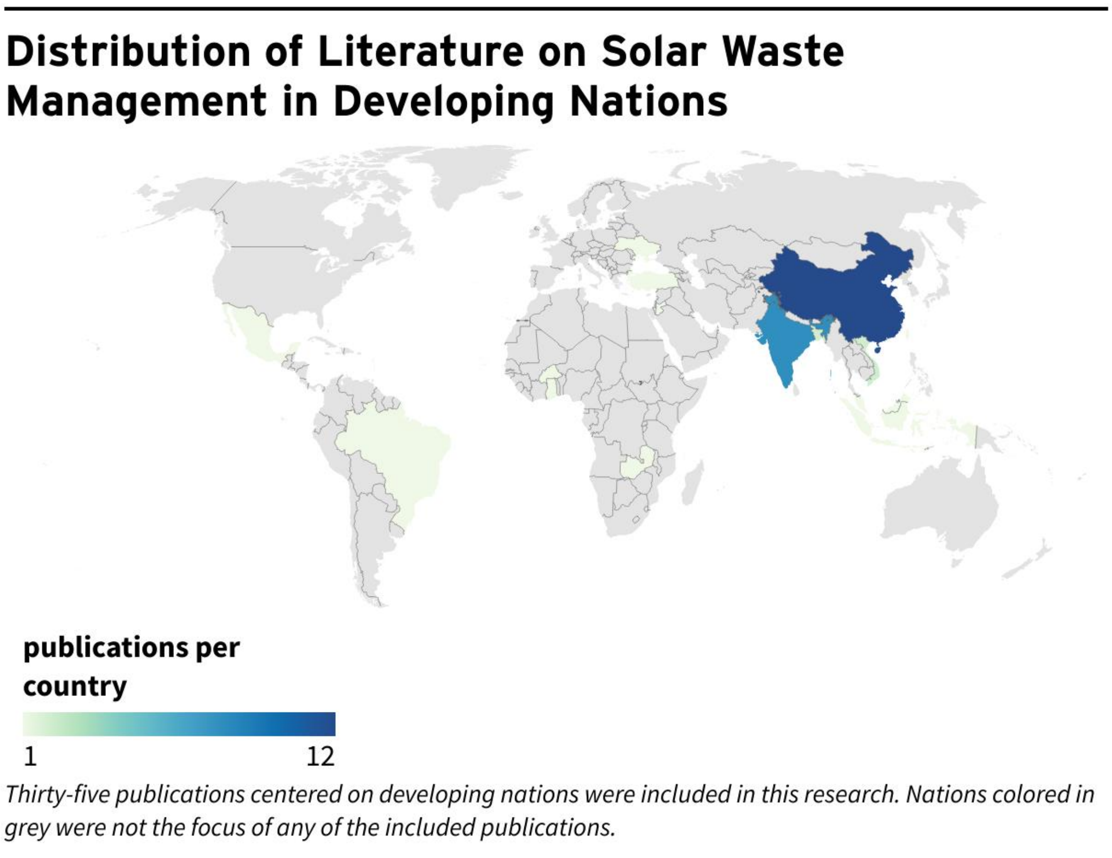

Figure 6: The geographical distribution of literature selected for inclusion in this research paper.

Country	No. of Relevant Publications Included
China	12
India	8
Bangladesh	2
Vietnam	2
Brazil	1
Burkina Faso	1
Ghana	1
Indonesia	1
Jordan	1
Malaysia	1
Mexico	1
Taiwan	1
Turkey	1
Ukraine	1
Zambia	1

Table 3: The number of publications included in this research sorted by country.

4.2 Temporal Trends in Literature

In general, the topic of solar waste management has mostly garnered attention since IRENA's 2016 publication "End-of-Life Solar PV Panels," which presented the first-ever projections of solar modular waste to 2050 (IRENA, 2016). All the publications included in this research were published between 2017 and the first quarter of 2024. Over this period, the number of articles published each year continuously increased. This suggests growing interest from the academic community in managing solar waste in specifically developing nations. Based on the current trajectory, the number of relevant publications issued in 2024 should meet or exceed that of 2023.

Between 2017 and the beginning of 2024, the number of continents represented in the literature also increases. In 2017, two published articles respectively discuss Mexico and Malaysia. China and India are the only two nations represented between 2018 and 2021. From 2022 onward, Asia continues to receive the majority of academic attention. However, single studies also represent Ghana, Brazil, and Ukraine, for example.

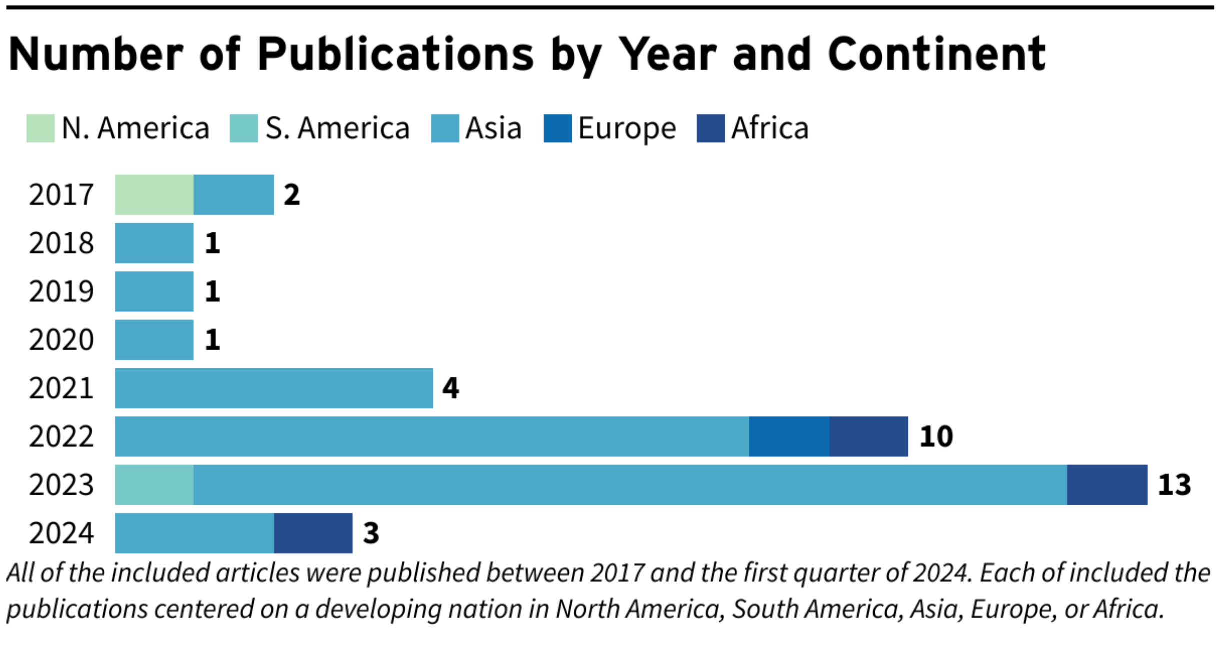

Figure 7: The distribution of literature selected for inclusion in this research paper by publication year and continent studied.

4.3 Methodological Distribution of Literature

Lastly, the frequency of each research methodology employed in the included publications was reviewed. Examining the research approaches applied in the existing literature can illuminate cross-disciplinary conclusions. It can also identify gaps in the body of knowledge.

For 15 publications, the methodology involved modelling or simulation This category includes life cycle assessments of solar modules, evolutionary game analysis of China's photovoltaic industry, and optimization of solar waste recycling networks, among others. Nine publications were classified as reviews; they summarized and synthesized the state of solar waste management in a specific nation. These reviews covered Jordan, China, Ukraine, India, Malaysia, Bangladesh, and Ghana.

Six publications were classified as case studies and utilized interviews and stakeholder analyses to determine perspectives on solar module waste. Five publications conducted cost-benefit analyses of solar module recycling and recommissioning. The conclusions were used to determine economic feasibility of these policies in Taiwan, China, India, and Bangladesh.

Research Methodology	Description
Review	A study that reviews and analyses the progress of current research
Model or simulation	A study that uses a model from mathematical functions for decision-making purposes
Case study	A study that uses qualitative data to examine a problem
Cost-benefit analysis	A study that assesses the economic efficiency of a project through the systematic prediction of costs and benefits

Table 4: Category for research methodology classification (Salim et al., 2019; Worcester Polytechnic Institute, 2023)

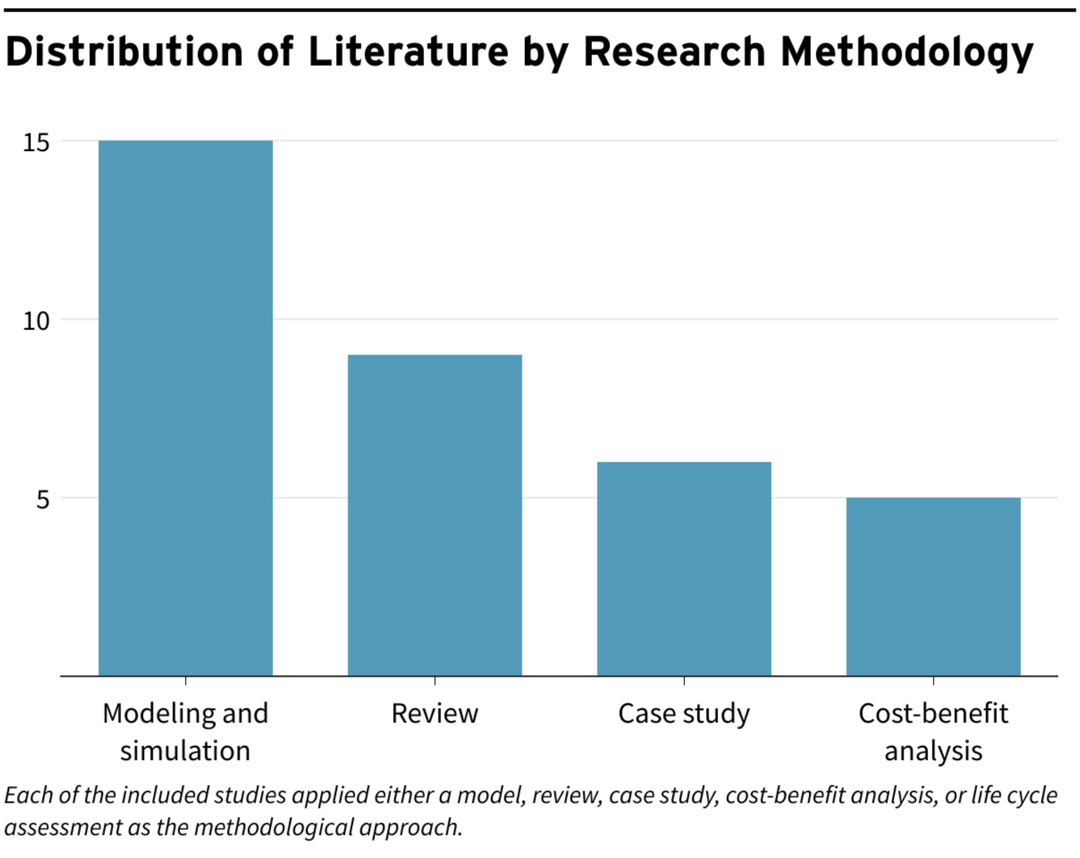

Figure 8: Distribution of included articles by research methodology.

4.4 Content Analysis of Literature

Each of the 35 included publications answered at least one of the following questions:

a. What is the forecast of solar module waste in the developing nation(s) and/or the status of solar waste management?
b. What is the challenge(s) in the nation hindering or preventing solar waste management?
c. What is the potential solution(s) that present a pathway either around or toward eliminating challenges to solar waste management?

Overall, challenges, which included policy, economic, and technological obstacles to solar waste management, were the most studied topic. Twenty-three of the 35 publications discussed challenges in-depth. Research into challenges is essential to comprehensively understanding a problem. It is also the first step in designing targeted, effective solutions.

The scope of solar panel waste in developing nations was the second most-discussed topic. Twenty-two studies forecast the volume of solar modular waste or reviewed the relevant figures and facts for a particular geography. Collectively, this research demonstrates that accumulation of solar module waste presents a new and pressing environmental challenge, particularly in developing nations where strategies for management are less robust or non-existent (Mahmoudi et al., 2019).

Potential solutions for solar waste management in developing nations was the least studied topic in the literature. The potential solutions are the keys to overcoming understood challenges. They describe research-based mechanisms for effectively facilitating solar module waste management.

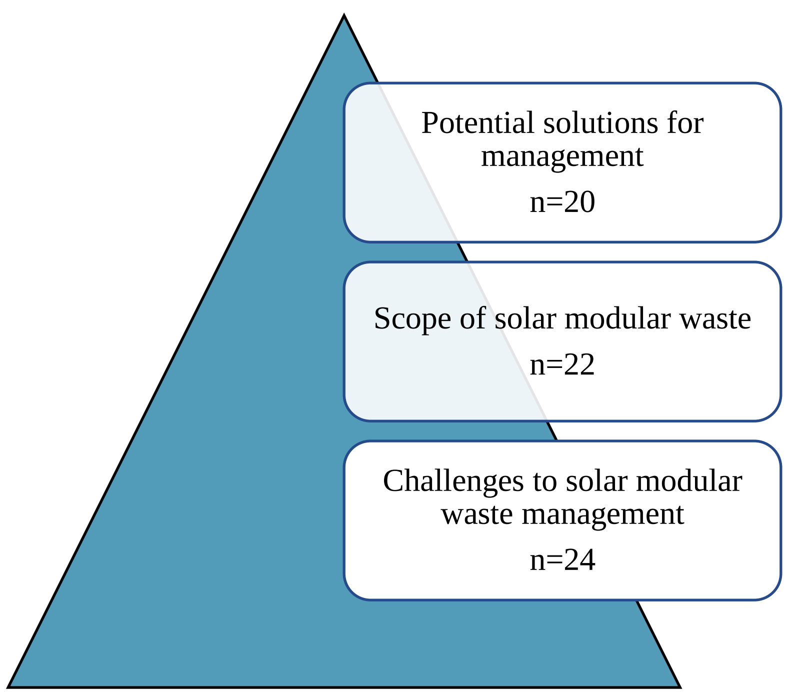

Figure 9: Hierarchy of topics addressed across the 35 publications. Multiple publications discussed more than one of the research questions.

During open and selective coding of the publications, each overarching challenge and potential solutions was clustered under one of three categories:

a. Policy: this category refers to national, local, and corporate policies, practices, and regulations that will hamper or facilitate the implementation of solar module waste management.
b. Economic: this category refers to market and financial factors that present obstacles or create conditions for solar module waste management.
c. Technological: this category refers to the technical feasibility of solar module recycling and recommissioning, as well as the potential development of new products and systems.

Table 5 presents the list of the resounding challenges demonstrated throughout the literature by category. Table 6 includes the list of potential solutions by category.

Category	**Challenge**	**No. of References in the Literature**
Policy	There are no specific regulations in place regarding solar waste management.	4
	There is a general lack of consumer or stakeholder awareness and participation in solar waste management.	2
	There are few or no economic incentives to promote investment in solar waste management activities.	7
Economic	There is an insufficient quantity of solar module waste to make the recycling or recommissioning process profitable.	2
	There is a lack of coordination and information sharing among solar producers and recyclers due to market competition.	6
	There is a lack of adequate infrastructure needed to support collection and recycling or recommissioning programs.	2

Technological	Physical and/or chemical differences among end-of-life solar modules limit the feasibility of recycling and recommissioning.	1

Table 5: Challenges for solar module waste management in developing nations.

Category	**Potential Solution**	**No. of References in the Literature**
Policy	Introducing regulations that hold solar module producers responsible for the waste that their products become.	4
	Providing economic incentives to increase solar module collection and recycling.	2
	Engaging in public-private partnerships that make solar module recycling more affordable and attractive.	2
Economic	Implementing a take-back or collection scheme that allows consumers to return their products for recovery and recommissioning.	2
	Optimizing the number and type of collection centers and recycling plants.	4
Technological	Requiring research and development on new efficient and cost-effective recycling techniques.	4
	Creating an open-access, knowledge-sharing platform.	2

Table 6: Potential solutions for solar module waste management in developing nations.

5. Discussion

5.1 Challenges

There are policy, economic, and technological challenges impeding the development of solar panel recycling and recommissioning in developing nations. The most cited challenge in the literature is that there are few or no economic incentives to promote investment in solar waste management. In the absence of economic incentives, such as subsidies or tax breaks, the economic feasibility of solar module recycling is low (Zhang et al., 2022). This is due largely to the high depreciation of fixed assets from the relatively small waste scale and the immaturity of nascent recycling technology (Li et al., 2023). In a case study by Nain and Kumar (2022), the lack of financial incentives means most manufacturers are reluctant to invest in take-back schemes or recycle panels. Ninety percent of the solar manufacturers surveyed in the study, which was performed in Greater Noida, India, reported selling their defective or decommissioned modules to secondhand sellers or informal recyclers.

The second most common challenge to solar module waste management in developing nations is the lack of coordination between producers and recyclers. Producers are reluctant to share proprietary information. In the absence of information, recyclers face challenges in recovering valuable resources and decommissioning module components (Salim et al., 2019). The lack of coordination will result in modules being taken to landfills or having components manually removed (Ndzibah et al., 2022). Additionally, the lack of accountability and coordination among producers and recyclers makes it a challenge to develop and enforce recycling regulations or guidelines (Jain et al., 2022).

Third, the lack of appropriate regulation regarding solar waste management is a core challenge hindering recycling and recommissioning. In a case study by Chisumbe et al. (2022), a structured questionnaire taken by a purposive sample Lusaka, Zambia concluded that there is a lack of regulation and policy on solar waste. This contributes to improper disposal, including throwing modules in bins or pits, which can be harmful to the environment. A review by Jain et al. (2022) stated that the lack of regulation culminates in “immense ambiguity” and impedes a streamlined process for collection, transportation, recovery, and recycling.

5.2 Potential Solutions

Introducing regulations and policies promoting extended producer responsibility was the most referenced solution in the policy category. Extended producer responsibility would hold producers of solar modules responsible for managing post-consumer waste. The concept is the basis of the WEEE directive in the EU, which is the only example of a national or international solar waste-specific policy (IRENA, 2016).

Research performed by Yu and Tong (2021) concluded that extended producer responsibility regulations are fundamental to effective and cost-efficient solar waste management. Extended producer responsibility encourages producers to cooperatively establish recycling systems and infrastructure (Yu and Tong, 2021). A study by Sharma et al. (2023) affirms that extended producer responsibility legislation is necessary to promote a circular economy.

In the economy category, implementing a take-back or collection scheme for returning end-of-life modules was the most cited potential solution. A collection scheme positively influences consumers' willingness to return decommissioned modules by increasing access to collection centers (Salim et al., 2019). Collection schemes can also help overcome financial barriers by centralizing large quantities of solar module waste, which, in turn improves the profitability of recovered materials recycling (Kabir et al., 2023).

In the technological category, requiring research and development on new recycling technologies was the most cited potential solution. Research and development projects can be undertaken to establish new recycling approaches for solar modules and commercialize their adoption (Jain et al., 2022). Additionally, research and development can help establish a more holistic framework for waste management (Yu et al., 2023).

6. Recommendations for Future Research

Based on this qualitative systematic review, it is clear that research on solar waste management in developing nations is centered on China and India. Investigating the challenges and potential solutions for solar waste management in China and India is critically important. Per IRENA's projections, China and India are poised to accumulate among the largest volumes of solar modular waste, and currently have no regulatory frameworks for management (IRENA, 2016). However, there is a need to increase the geographic scope of research to Latin America, Africa, and the Middle East. More contributions are needed from developing nations on these continents in order to best forecast the solar modular waste flows and design proactive strategies (Mahmoudi et al., 2019).

Additionally, more analysis from developing nations in Latin America, Africa, and the Middle East can support suitable investment conditions. In order to motivate investment in recycling infrastructure, demonstrating a considerable amount of solar waste is needed. Current and substantiated reporting, with volumes of waste produced at the national level, can provide this information. Further research to assess value creation in secondary markets will also simulate market growth for solar module waste (IRENA, 2016).

Furthermore, there is need for socio-political research to gauge consumer perceptions on solar module waste management. Of the 35 publications examined in this research paper, only two employed interview approaches, one in Lusaka, Zambia and the other in Greater Noida, India. Each revealed general concern regarding how solar waste was being landfilled or disposed of by the informal recycling sector (Chisumbe et.al, 2022; Nain and Kumar, 2023). Within a decade, the massive increase in solar waste volume will likely stir up further concerns and social debate. Socioeconomic and political research can preempt this challenge (Salim et al., 2019).

Lastly, current methodological approaches to the research topic are strongly biased toward modeling and simulation, with a particular emphasis on life cycle assessment and forecasting. These methods are not necessarily best suited to examining the dynamic and complex systems of solar waste management. Modelling that incorporates feedback mechanisms, such as discrete event simulation and system dynamics, are better at capturing relationships between stakeholders and events (Salim et al., 2019). On-the-ground experiments are also important to revealing real-world behaviors and actions. They are useful in illuminating unanticipated problems and can proffer best policies and practices for solar module waste management.

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