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Review

The necessity for end-of-life photovoltaic technology waste management policy: A systematic review

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ABSTRACT

Photovoltaic (PV) technologies in the energy industry are crucial for transitioning to a decarbonized era that relies on renewable energy sources. This systematic review aimed to identify the potential environmental impacts associated with the entire life cycle of PV technologies. To accomplish this, the review analysed literature from the last five years focused on life cycle assessment and evaluating PV technologies' environmental impacts/toxicity. In total, 72 final articles were collected and analysed, considering the year of publication, research methodology, and geographical context. Although there is substantial knowledge regarding potential impacts associated with end-of-life (EoL) PV technologies, only a limited number of regions have specific regulations regarding PV waste. With the incorporation of circular economy principles, targeted strategies for EoL treatments can be developed and implemented, leading to a substantial reduction in the environmental impacts caused by EoL PV modules, where this aspect represents a critical concern within the context of PV technologies. Therefore, this study emphasises the need to integrate life cycle assessment, circular economy, and systems thinking to achieve more sustainable development when utilizing PV technologies so that the diffusion of PV technologies helps decarbonization transitions without creating major unintended environmental problems in waste systems.

1. Introduction

In recent years, the adoption of photovoltaic (PV) systems has experienced a significant rise worldwide, driven by the proliferation of solar farms, PV installations, and building-integrated photovoltaics (BIPV) (Yu et al., 2022). This trend is expected to continue as the global population and energy demand continue to grow (Venkatachary et al., 2020), and more countries seek to transition to decarbonized energy systems. Compared to other renewable energy sources like hydro and wind, PV technology is considered to be more reliable and affordable and has a higher potential for achieving their respective energy production (Maani et al., 2020). To date, China leads the global PV market in terms of advancement (Xu et al., 2018), with the United States, Japan, and India following closely behind.

Though PV technologies do not pose significant adverse impacts during the operation phase, the modules contain hazardous materials where simple disposal methods like landfilling will enhance the risk of human and environmental harm. Despite the estimated life span of PV modules being approximately 25–30 years (Mahmoudi et al., 2020), projection indicates PV wastes will reach 8 million tons (Mt) by 2030 and approximately 80 Mt by 2050 (Tan et al., 2022), and can pose significant environmental problems (Heath et al., 2020). PV technologies have received a substantial amount of attention to date. However, there is still a lack of specific regulations governing the disposal or management practices of end-of-life (EoL) PV modules and fostering recycling management around the world (Nain & Kumar, 2020). Prior studies have investigated the environmental impacts of PV technologies using the life cycle assessment (LCA) method. The identified impacts span all key life cycle stages, including production, operation, and EoL phases, collectively resulting in significant environmental burdens. Notably, the EoL phase, predominately landfill disposal, exerts the most pronounced impact, encompassing greenhouse gas (GHG) emissions, eutrophication, freshwater toxicity, human toxicity, and resource depletion (Tawalbeh et al., 2021). Thus, to mitigate the potential adverse impacts of waste generated from PV materials, Duflou et al. (2018) stated that it is critical to develop waste management systems. Gahlot et al. (2022) have conducted research that indicated that valuable PV materials can be recovered by implementing a recycling process, and a closed-loop

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supply chain can be established with the aim to reduce or eliminate the waste associated with the diffusion of PV. However, the prevailing method for treating EoL PV waste remains landfill disposal, with recycling as a less common alternative. The absence of policies and regulations, coupled with the extensive proliferation of PV technologies, collectively result in significant environmental impacts. Remarkably, even in China, a region leading in the PV market and responsible for the majority of PV production and installations, specific regulations for PV treatment have yet to be established. With the rapid expansion of PV technologies, it is imperative to address these issues promptly and devise effective solutions to prevent further escalation of landfill disposal, which can lead to detrimental environmental consequences.

This review then focuses on identifying the disposal and management methods of PV technologies. Addressing this question will be able to gain insight into two key aspects: 1) the variation in disposal and management practices across different geographical locations and policy settings, and 2) how these disposal and management methods mitigate/prevent the unintended environmental impact in waste systems of the diffusion of PV.

2. Methodology

We conducted a systematic literature review to identify the paradoxes behind the wide dissemination of photovoltaic cells, which can

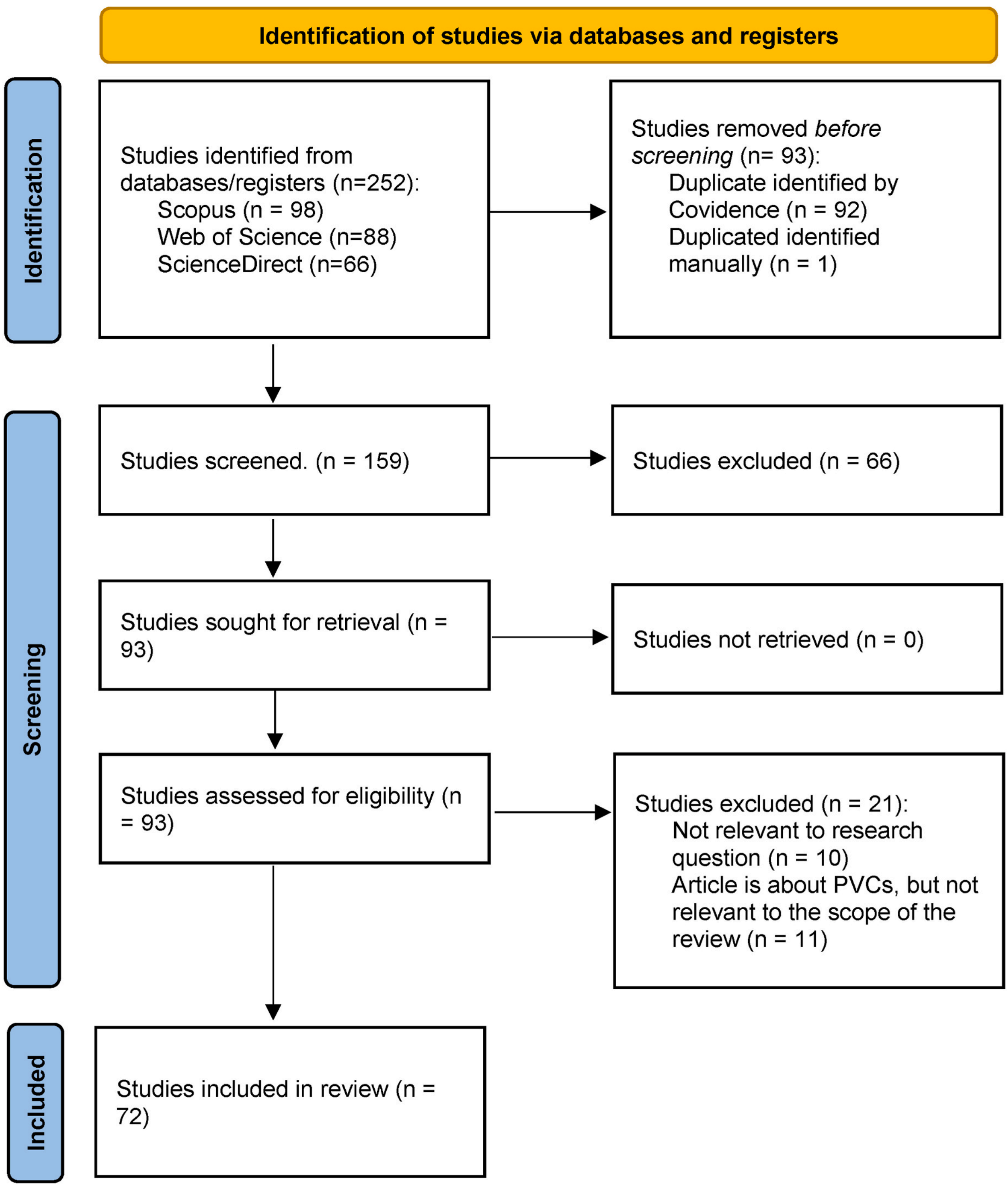

Fig. 1. PRISMA 2020 flow diagram for systematic review for SCOPUS, Web of Science and ScienceDirect database.

contribute to decarbonizing energy systems, and the life cycle methods and system modelling and analysis critical to mitigating its associated waste footprint.

A systematic review uses transparent and replicable procedures to determine, choose, and evaluate pertinent research and gather and analyse data from the studies included in the review (Moher et al., 2009). It identifies knowledge gaps by assessing combinations of study locations, subjects, variables, and results. The review follows a structured, stepwise approach to gathering and analysing the literature, encompassing several distinct processes (Pickering and Byrne, 2014) that minimize bias (Brewerton and Millward, 2001).

In this section, we outline the methods used to collect, analyse, and present the data in this paper. The initial stage in the methodology involves the identification of criteria required to select appropriate papers for the review. The following step involved using Covidence software as a screening and extraction tool. Duplicates were removed both automatically on Covidence and manually to avoid errors. The third step then focused on evaluating each paper's applicability for the study to determine its fit with the topic and scope through a title and abstract screening. The final step involved conducting a comprehensive full-text review of the selected articles. During this stage, relevant findings were noted within the content analysis framework and presented in Appendix A2. Fig. 1 below illustrates the search process utilized in this review.

2.1. Search criteria

In Table 1, the initial stage of the systematic review includes the identification of which studies should be included and excluded. In order to achieve this, a meticulous and transparent search process was conducted to identify articles relevant to the search strings. The review focuses mainly on "photovoltaic cell" or "solar panel". Other vital keywords considered in this review include "resource management", "waste management", "recycle", "life cycle assessment", and "circular economy".

The study utilized data retrieved from validated databases, which include Scopus, Web of Science (WOS), and ScienceDirect. Only formal literature, which contains articles and peer-reviewed literature, was considered for inclusion in this research project, excluding books and other types of literature.

To address the research questions put forth in this review, the criteria for inclusion and exclusion were carefully selected based on the following factors:

I. *Access type and document type*: The study exclusively selected articles that were available and are published articles and reviewed literature, in the Scopus, Web of Science and ScienceDirect databases. Grey literature was not included.
II. *Year of Publication*: To ensure that the articles selected are recent and relevant studies and data, the search was limited to articles published in the last five years (2018–2023).
III. *Language:* Only articles that appeared using the search string and were written in English were selected for review.

2.2. Article search

In the second stage of the systematic review process, conducted in March 2023, 252 articles were gathered from the SCOPUS, Web of Science (WOS), and ScienceDirect databases, with 98, 88, and 68 articles, respectively. All articles that met the inclusion criteria and fit the scope of the research area were collected. Of the 98 papers from Scopus, 86 were published articles, and 12 were review papers. For WOS, 24 gathered papers were review articles, 2 were early access articles, 38 were open access articles, and eight were enriched cited references. For ScienceDirect, 51 were research articles, and 16 were review articles.

The criteria of inclusion stated in the previous section were manually inputted within the database search. Thus, the articles gathered should be within the criteria. The manual screen at this stage ensured that articles were pertinent to the research project, eliminated search errors and excluded articles that met the exclusion criteria or were irrelevant to the research questions. This includes articles that were overly technical in discussing PV modules, with a strong focus on the mechanical aspects, and those that were unable to provide answers to the research questions.

2.3. Article evaluation and inclusion

During this stage of the systematic review, 252 papers were collected and evaluated manually to ensure they were within the scope of the research project. Ninety-two duplicates were removed automatically on Covidence, and an additional duplicate was removed manually. The remaining 159 articles were then subjected to further title and abstract screening to remove those that were irrelevant or did not contribute to the research project. Articles that had a relevant sub-theme were included. In total, 66 articles were removed, leaving a sample of 93 articles for examination.

2.4. Article content analysis and results

The last stage of the systematic review involved a full-screen review of the 93 articles obtained from the previous stage. During this stage, 21 articles were excluded, with ten being irrelevant to the research question and 11 being overly technical on PV modules, which focused on the mechanical components of the PV modules and did not contribute to the scope of the research project. The remaining 72 articles constitute the final sample for this review and are listed in appendix 1 along with the content analysis conducted.

3. Results

This section analysed the sample of 72 articles in regard to the year of publication, research methodology employed, and the geographical context of each selected article for the review.

3.1. Paper distribution by year of publication

Fig. 2 depicts the paper distribution of the selected 72 papers by their year of publication. The figure shows a gradual rise in the number of papers selected between 2018 and 2022. The increase in publications indicates a growing interest and concern about the potential

Table 1
Database search strings.

Databases	Search String	Date
Scopus	(TITLE-ABS-KEY (("resource management" OR "waste management " OR (circular AND econom*) OR recycl*)) AND TITLE-ABS-KEY (((photovoltaic AND cell*) OR (solar AND panel*))) AND TITLE-ABS-KEY (("system dynamics" OR "life cycle assessment" OR "life cycle analysis")))	March 16, 2023
Web of Science	((TS=("resource management" OR "waste management " OR "circular econom*" OR recycl*)) AND TS=((photovoltaic AND cell*) OR (solar AND panel*))) AND TS=("system dynamics" OR "life cycle assessment" OR "life cycle analysis")	March 16, 2023
ScienceDirect	Title, abstract, keywords: ((photovoltaic AND cell?) OR (solar AND panel?)) AND ("resource management" OR "waste management " OR "circular economy" OR recycle)) AND ("system dynamics" OR "life cycle assessment" OR "life cycle analysis")	March 16, 2023

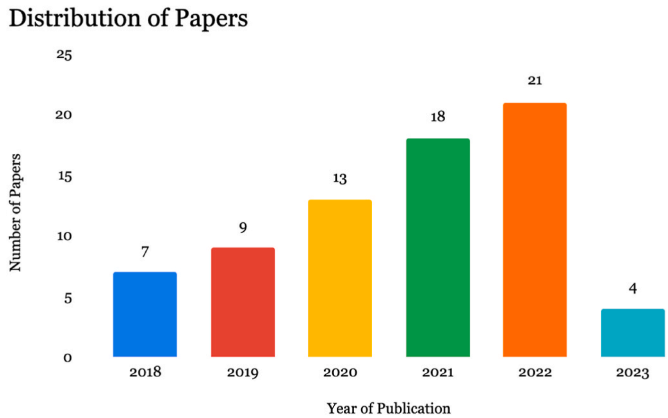

Fig. 2. Distribution of selected articles by year of publication.

environmental consequences of PV. It also reflects the rising attention given to integrating circular economy principles and applying LCA in models and studies.

3.2. Research methodology

The result of the methodology used in the selected 72 papers is presented in Fig. 3. Seven research methodologies were identified in selected studies: models, reviews, theoretical and conceptual papers, case studies, surveys, and experimental papers (Table .2). The research methodology most frequently used in the selected article was models, followed by reviews, theoretical and conceptual, survey, case study, and finally, experimental methodology.

Based on Fig. 4, the prevalent approach adopted for PV technologies is LCA, followed by CE, and SD methods being less commonly employed. This indicates a growing trend towards incorporating LCA in PV technologies to promote more sustainable development.

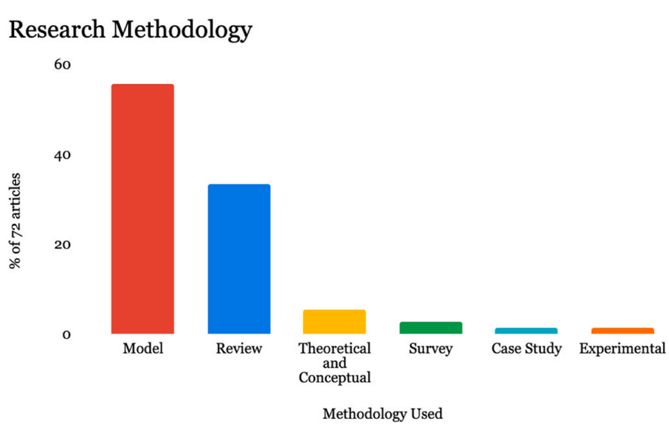

Fig. 3. Percentage of research methodology cited in selected articles.

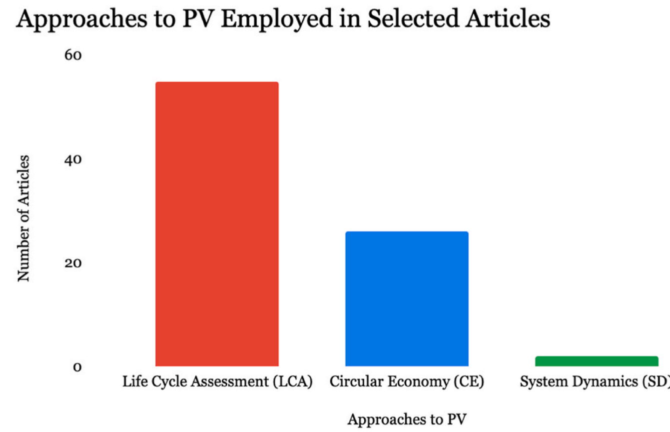

Fig. 4. Approaches to PV employed in selected articles.

3.3. Geographical context

The study's geographical context refers to the geographical region where it is being conducted and the different geographical regions mentioned in each paper. The paper included four different regions: Asia, Europe, Oceania, and Americas, which are illustrated in Fig. 5. The term "Worldwide," as shown in Fig. 5, refers to articles that studied all or a large majority of countries globally without specifying any particular country or region. Additionally, the term "Americas" encompasses North, South, and Central America collectively.

As shown in Fig. 6, a significant number of Asia were cited for India, including a minority for Thailand and Malaysia. Surprisingly, no articles were dedicated to China regarding its advanced development in the PV sector.

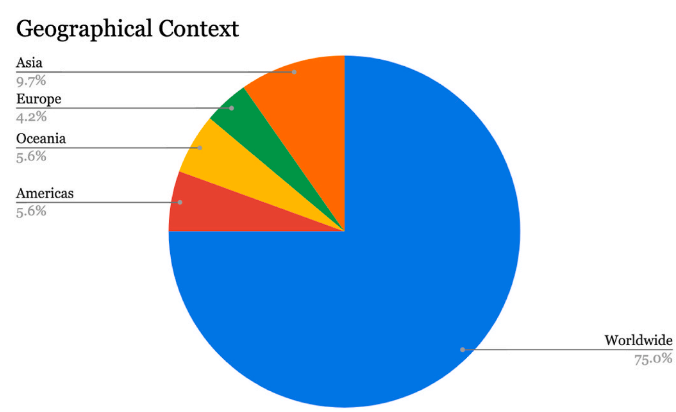

Fig. 5. Percentage of geographical context cited in selected articles.

Table 2
Classification category and definition for research methodologies.

Research Methodology	Definition
Model	A study that employs mathematical functions as a model for decision-making objectives, such as life cycle assessment and system dynamics (Salim et al., 2019a)
Review	A study that examines and assesses the developments in existing research (Salim et al., 2019a)
Theoretical and Conceptual	A study that deliberates on theories or conceptual frameworks (Salim et al., 2019a)
Case Study	A study that utilizes qualitative data to explore an issue or a case (Salim et al., 2019a)
Survey	A study that is facilitated by data collected through face-to-face interviews with experts within the field or questionnaires (Salim et al., 2019a)
Experimental	A study that employs a scientific and systematic methodology to manipulate one or more variables for a desirable result (Salim et al., 2019a)

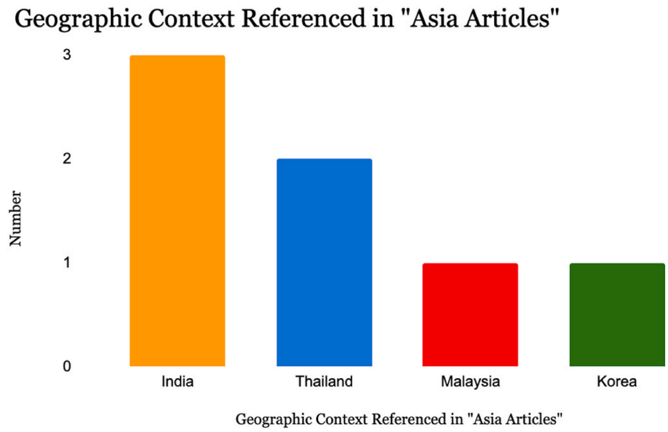

Fig. 6. Number of geographic context referenced in "Asia articles".

4. Discussion

This section presents the main components of the research that align with the research scope and address the research questions.

4.1. Life cycle assessment (LCA)

The findings of the conducted review highlight that the adverse impacts associated with deployment of PV technologies have been comprehensively explored and analysed through the use of LCA (Fig. 4.). Krebs-Moberg et al. (2021) has stated LCA as a reliable methodology to evaluate the environmental aspect and associated impacts of a product. Typically, it entails creating an inventory of the relevant inflows and outflows of materials of a product system, assessing potential environmental implications related to those flows, and interpreting the findings of the impact assessment and inventory analysis phases (Mahmoudi et al., 2020). The LCA method comprises four distinct phases, including the goal and scope definition, the life-cycle inventory analysis, the life-cycle impact assessment, and the interpretation steps (Liu et al., 2021). To date, the use of LCA methodology to quantify the potential adverse environmental implications of PV technologies has raised (Amarakoon et al., 2018). Briese et al. (2019) has conducted LCA studies that indicates PV technologies can cause detrimental environmental implications such as acidification, eutrophication, and ecotoxicity, as a result of multiple processes occurring throughout their life cycle.

Given the widespread use of LCA to evaluate PV technologies, it can be confidently stated that the related impacts have been thoroughly addressed, thereby drawing the attention of pertinent authorities. However, it's important to note that the sole use of LCA method can only determine the magnitude of these impacts, without delving into their root causes or proposing solutions.

4.2. Circular economy (CE)

The circular economy is a different approach to the current "make, use, dispose" industrial model, which depletes natural resources (Colarossi et al., 2022). The circular approach involves a set of reparative activities throughout the supply chain. Deng et al. (2022), Maceno et al. (2022) has indicated that by maintaining materials in use, a circular approach can eliminate waste and toxicity, maximize system utility, preserve materials, energy, and value, and conserve natural resources by reducing resource depletion. Colarossi et al. (2022) has further supported the idea that beyond simply recycling materials, a circular economy integrates life cycle thinking and systemic regeneration efforts to meet societal requirements without depleting financial, environmental, and other resources for future generations.

4.2.1. Circular economy of PV technologies

In order to achieve sustainability and reduce the environmental implications of PV technologies, the PV industry must implement a circular economy model. This approach places a strong emphasis on the idea of maximising resource value, minimizing waste and pollution (Rabaia et al., 2022). Zubas et al. (2023) has stated that while silicon is the most widely used material in PV technologies, there has been limited research conducted on its potential for circularity. Processes associated with silicon, including mining, purification, and smelting, has a comparatively greater environmental consequence when compared to other materials utilized for the production of PV modules (Xu et al., 2018).

Integrating a circular economy is a necessary and effective approach in order to minimize the associated environmental implications of PV modules. Proposed circular practices for the PV industry involve minimizing material usage during the manufacturing and module production phases, prolonging module lifespan through the implementation of durable materials and reuse methods (Sheoran et al., 2022), reconditioning module components, reutilizing modules for secondary usage (Khalifa et al., 2022). By enhancing module efficiency and lifespan, these circular techniques not only reduce waste and advance resource efficiency but also create value by enabling more power generation from fewer raw materials.

4.3. System dynamics (SD)

Modelling based on systems thinking (ST) has become a popular method for analysing the complexity of specific issues and has been used to several environmental studies (Sahin et al., 2016). The ST technique uses feedback theory to create a dynamic hypothesis that explains and forecasts the behaviour of the system in both the past and the future (Swanson, 2002). With the incorporation of mathematical models and computer simulations, SD is a multidisciplinary methodology that allows a better understanding of the behaviour of complex systems, such as social and ecological systems (Swanson, 2002). SD modelling also enhances greater success when influencing public policies, aiming to better equip decision-makers for decision-making (Papachristos, 2019).

The development of the SD model involves two primary steps: problem scoping and CLD modelling. Problem scoping is the initial step to gather insights from relevant stakeholders regarding the inner workings of a specific system, the supply chain, existing challenges, drivers, and plausible management strategies (Salim et al., 2020). The second step, CLD, is used in SD for illustrate the causal relationships among the variables identified during the problem-scoping phase. During the creation of the CLD, two types of causal relationships are considered, indicating the direction between a pair of variables. A positive (+) causal relationship signifies that the cause-and-effect variables move in the same direction, where an increase in the cause variable leads to an increase in the effect variable. Contrarily, a negative (−) causal relationship suggests that the cause-and-effect variables move in opposite directions, where an increase in the cause variable results in a decrease in the effect variable. The incorporation of double lines across the arrows symbolises information delay, signifying the time lag between the cause and its effect (Salim et al., 2020). The strength of this model is that it aids stakeholders in testing assumptions and challenging established mental models, which results in a critical and paradoxical understanding of system structure and behaviour (Hovmand, 2014). This integrated participatory modelling approach has demonstrated various benefits, including the validity of model outputs (Kotir et al., 2017), promoting the acquisition of pertinent knowledge for stakeholders (Stave, 2010), and proposing potential courses of action for policies (Salim et al., 2021).

To date, the PV sector has been extensively studied using SD modelling. However, the focus was on other aspects of the sector rather than EoL PV technologies (Marcuzzo et al., 2022). As indicated by Fig. 4., only 2 out of 72 selected articles — have used SD modelling in their research on PV technologies. This highlights a crucial weakness in using SD models to analyse the intricate interaction of "cause" and "effects" variables inherent in the adoption of PV technology. To date, relevant authorities should be aware of the externalities associated with the implementation of PV technologies, still, the development of a viable solution and stringent relevant regulations are yet to be seen. One could say that this indicates the lack of understanding of this complex system; limited SD modelling impedes a deeper exploration of the "cause" of these impacts. For instance, identifying the specific stages of the life cycle of PV technologies that are the most significant contributors to environmental harm; or identification of variables, e.g. policies and regulations or financial support, that would exert the most substantial influence in addressing this issue.

4.4. Global PV waste projection and EoL management

The amount of waste generated by PV modules is anticipated to increase exponentially, potentially 60 to 70 million tonnes (Mt) by 2050 (Oteng et al., 2021) Additionally, due to hazardous materials in PV modules, there is a significant adverse impact on human and environmental health, which will be examined in greater detail in the following section. At present, only the European Union and the United States have adopted specific regulations for PV waste treatment (Nain & Kumar, 2020). In contrast, countries such as China, Japan, India, have not yet established specific regulations for managing PV waste (Gahlot et al., 2022).

4.4.1. China

To date, China is the leader in the PV market (Xu et al., 2018). However, there are no particular criteria regarding the treatment of EoL PV modules. Although the Chinese government released the Regulations on Recycling Management of Electrical and Electronic Products in 2009, which mandated the collection and recycling of electronic waste through a centralized management system, the processing guidelines specified under regulation did not incorporate PV waste within the list (Daniela-Abigail et al., 2022). It's estimated that by 2050, the country could reach 22.34 Mt of PV waste at EoL (Marcuzzo et al., 2022). This holds particular significance for China, as it holds a leadership position in the PV market, resulting in the highest number of PV installations compared to other regions. The absence of specific policies and regulations governing the EoL treatment of PV waste could lead to a significant increase in landfill disposal, causing substantial environmental harm. Conversely, being a leader in the PV market, taking proactive measures in the EoL treatment of PV waste would set an example for other regions to follow, thus promoting proper EoL treatments for PV waste.

4.4.2. Japan

In Japan, the PV market is well-established, but there are currently no specific regulations regarding PV waste. In general, the region lacks particular infrastructure and legislative frameworks for recycling PV modules at EoL (Chowdhury et al., 2020),where there are no preparations to dispose of them in a secure and efficient manner. However, joint assessments have been conducted since 2013 to determine the proper disposal of EoL renewable energy technologies, including PV waste, solar water heaters, and wind turbines. It is estimated that by 2030, Japan could generate 2.1 Mt of EoL Pv waste. By 2050, this number could increase to 3.22 Mt (Marcuzzo et al., 2022).

4.4.3. India

Despite the Electronic Waste Management and Handling Rules (2016) to address general electronic waste requirements and restrict the utilization of harmful materials in electronic goods, which solely apply to the commercial electronic waste recycling infrastructure within the country, there are no policies or guidelines established for the recycling and recovery of EoL PV (Sheoran et al., 2022). As a result, PV modules is often disposed of in unscientific and inadequate ways, even though there are well-established infrastructure to recycle e-waste within the country (Daniela-Abigail et al., 2022). It is projected that a minimum of 18.18 Mt of EoL PV waste could be generated by 2050 (Marcuzzo et al., 2022).

4.4.4. The United States

In the United States, the PV market is well-established and rapidly growing. Yet, there are currently no defined regulations pertaining to the disposal of waste generated from PV systems. The country does not have adequate policies, incentives, and regulations in place to facilitate the recycling of EoL PV wastes, excluding Washington, California, and North Carolina. PV modules at EoL must be discarded in accordance with the Resource Conservation and Recovery Act (RCRA) of 1976, which is the legal framework that outlines the guidelines for managing solid waste that is both hazardous and non-hazardous in the US (Dominguez and Geyer, 2019). However, this Act does not have specific requirements for PV modules. By 2050, the country is projected to produce around 5.29 Mt of EoL PV waste (Marcuzzo et al., 2022).

4.4.5. Australia

In Australia, the EoL PV modules have been identified as a key waste stream that is expected to increase in the coming years. Additionally, the Australian government has also implemented a new stewardship programme, stating EoL PV modules as waste electrical and electronic equipment (WEEE), which requires appropriate disposal treatments (Mahmoudi et al., 2020). Despite that recent regulations aids with the accumulation of PV waste, the country is projected to reach 3.6 Mt of PV waste by 2030, and this number could exceed 7.0 Mt by 2047 (Mahmoudi et al., 2019).

4.4.6. European Union

Through the identification of EoL PV modules into its WEEE Directive (Nain & Kumar, 2020), the European Union has adopted specific regulations for PV waste. Furthermore, the European Union Restriction of Hazardous Substances (EU RoHS) directive has played a pivotal role in promoting the appropriate end-of-life (EoL) treatment of PV waste by imposing responsibility on producers to recycle a minimum of 65–75% (by weight) of their modules once they reach the EoL phase (Nain & Kumar, 2020). Extended producer responsibility (EPR) is also implemented within the regulatory framework of the European Union, where it holds producers and importers accountable for collecting and recycling activities and facilitates the recycling of EoL PV panels by integrating recycling costs into the initial price of PV modules (Salim et al., 2019a). The region is anticipated to reach 9.5 Mt of EoL PV waste by 2050.

4.4.7. Global general waste policies

Given the intricate nature of PV module structures and recycling processes, specialized infrastructure, equipment, and multiple treatment stages are necessary for processing individual components of the module. General waste treatment policies, such as the RCRA in the United States, the Electronic Waste Management and Handling Rules 2016 in India, the Recycling Management of Electrical and Electronic Products in China in 2009 (Nain & Kumar, 2020) and the waste electrical and electronic equipment (WEEE) directive in Australia and the European Union, lack specific provisions and processes for the recycling of PV modules. Consequently, these policies fall short of regulating the EoL treatment of PV waste, as they cannot adequately support the unique recycling requirements of PV modules. For instance, the WEEE directive lacks a designated category for PV modules and does not have a specific collection target for these modules. Conversely, since these regulations do not explicitly address EoL PV waste, stakeholders are not legally compelled to recycle their EoL PV waste. Consequently, they often opt for the 'easier' approach, which is less time-consuming and less costly, namely, landfill disposal. This scenario is notably evident in India, where the region boasts a well-established infrastructure for recycling e-waste, yet a majority of their EoL PV modules still end up in landfills (Daniela-Abigail et al., 2022). This also underscores the importance of implementing specific regulations to facilitate the recycling of EoL PV modules.

4.5. Influences of policies on EoL treatments

Policies and regulations are vital in facilitating the proper EoL treatment of PV modules (Oteng et al., 2021). Users are only inclined to appropriately dispose of EoL PV modules if there's an incentive or a legally and financially supported framework, leading to a majority of EoL PV modules ending up in landfills. The enforcement of appropriate regulations would mandate all stakeholders in the supply chain to take responsibility for implementing the essential steps to recycle EoL PV modules. Extended producer responsibility (EPR) is the most prevalent product stewardship scheme that can be implemented for EoL PV modules, primarily for handling post-consumer electronic waste (Salim et al., 2019b). This regulation holds producers and importers accountable for collecting and recycling activities, where it facilitates the recycling of EoL PV panels by integrating recycling costs into the initial price of PV modules. The inclusion of EPR within its regulatory framework by the European Union (Piasecka et al., 2020) further emphasises the significance and effectiveness of this scheme. On the other hand, incorporating 'easy to disassemble' criteria into product design standards will also enhance the feasibility and cost-effectiveness of recycling EoL PV modules (Salim et al., 2019b).

Moreover, financial incentives significantly contribute to encouraging higher rates of recycling (Salim et al., 2019b). This could be attributed to the fact that the current recycling process lacks profitability for specific components of the PV module, primarily due to the associated expenses for equipment and transportation (Markert et al., 2020). In contrast, landfilling is often seen as a less time-consuming and economical alternative. To counterbalance this, the escalation of landfill costs would incentivise recycling, making it a more financially attractive alternative compared to the landfill disposal of EoL PV modules (Xu et al., 2018).

4.6. Environmental impacts of PVs

4.6.1. Landfill

During the life cycle of a PV module, the greatest quantity of ecotoxic substances arises from material handling and storage and components in landfills, and the disposal of PV modules in landfills is associated with the most significant negative impact (Piasecka et al., 2020). Although landfilling is a legal and predominant disposal method in many global regions, it can result in natural resource depletion, as well as air and soil pollution (Rathore and Panwar, 2022).

Improper handling of EoL PV modules can result in the release of pollutants, such as metals, leaching into the environment (Lunardi et al., 2018). Before landfill disposal, the PV module is typically separated from the balance-of-system (BOS) to sort out specific components by their waste types. The BOS consists of all non-module components of a PV system, such as inverters, switches, cables, fuses, ground fault detectors, and others. The environmental impacts of the BOS components primarily involve carcinogens and ecotoxicity, resulting from the emission of toxins and pollutants into the air and ground during their fabrication process and disposal in landfills, which can affect the water and soil, and lead to potential contamination (Zhong et al., 2011). Under full landfill disposal, the potential of human carcinogens can go up to 38, 900 kg 1,4-DCB (kilograms of 1,4-Dichlorobenzene) (Mahmoudi et al., 2020).

4.6.2. Land use

The implementation of PV technologies can result in the loss of cultivable land and other profitable land utilization (Zarzavilla et al., 2022), where appropriate land planning and distribution are necessary to ensure effective utilization of land for PV systems while minimizing conflicts with other activities, such as agriculture. PV projects typically require more land when compared to conventional fossil fuel projects (De Marco et al., 2014), and the construction phase can have a significant environmental impact on terrestrial land and habitats due to utilization of concrete and burdensome devices, and infrastructure connection (Tawalbeh et al., 2021). Landfill disposal of EoL PV modules also requires a significant amount of land use, stated by Mahmoudi et al. (2020), under full landfill disposal, EoL PV waste will take up approximately 26,400 m^2a crop eq (area time crop equivalent) of land use.

4.6.3. Improper disposal

Improper disposal of materials such as cadmium, lead, and polymer can have harmful effects on the environment and human health, including respiratory and both non-carcinogenic and carcinogenic effects (Mayer et al., 2021). Cadmium telluride (CdTe), which can be found in CdTe PV modules (Maani et al., 2020), can cause severe lung inflammation and fibrosis. At the same time, lead leaching of PV modules can enhance reduced plant and animal growth, biodiversity loss, and human health impacts such as kidney function impairment, and effects on both immune and nervous systems. The back sheet and encapsulants of PV panels are made of non-recyclable, fluorinated, and cross-linked plastics. When exposed to inappropriate waste managements, corrosive gases will be released through combustion processes, posing significant threats to both the ecosystem and humans. Other than common metals, manufacturers also use antimony (Sb) to enhance the stability and performance of PV glass whilst being highly effective in refracting light. Sb components can lead to adverse environmental impacts when PV modules reach their EoL stage and are exposed to wet conditions (Rathore and Panwar, 2022). Antimony trioxide (Sb_2O_3) is considered carcinogenic to humans, and elevated levels of Sb in the environment are toxic to aquatic life and plants, its tendency to bioaccumulate (Schileo and Grancini, 2021), and requires appropriate treatments to prevent potential impacts to occur.

4.6.4. Air pollution and climate change

Compared to conventional power generation systems, PV technology represents an eco-friendly energy source that inflicts considerably fewer effects on air quality and climate change (Tawalbeh et al., 2021). By reducing the demand for non-renewable resources such as fossil fuels, it has the potential to mitigate the environmental implications of energy production. During operational phase, PV systems do not emit carbon dioxide (CO_2), methane (CH_4), sulphur oxides (SOX), and nitrogen oxides (NOX) (Tawalbeh et al., 2021). However, apart from the operational phase, other phases of the PV system's lifecycle, including fabrication, transportation, installation, operation, and disposal, produced a non-negligible amount of emission. The fabrication phase is accountable for the majority of emission within all life cycle phases, followed by the construction and operation phase (Tawalbeh et al., 2021). Within the fabrication phase, the emission are resulted from the fabrication of aluminium and steel, along with the manufacture of glass, and the reduction process from silica to silicon (Alsema, 2012). The LCA conducted by Mahmoudi et al. (2020) indicated that under full landfilling scenario, PV waste has a 2 kg CFC11 eq (kilograms of trichlorofluoromethane equivalent) ozone depletion potential.

4.6.5. Hazardous materials emissions

Uctug and Azapagic (2018) discovered that the production of PV modules entails the utilization of several hazardous substances in processes such as PV cell extraction, semiconductor etching, and surface cleaning. These materials include gallium (Ga), silicon (Si), copper (Cu), cadmium (Cd), selenium (Se), and tellurium (Te) (Alami et al., 2020), where the majority of these materials are obtained as secondary products from the mining of alternative metals. For example, Cd is a by-product of the processing of lead and zinc minerals effluent; it is then purified and concentrated to the required purity for CdTe cell fabrication. On the other hand, Te is a by-product of mining several metals (Tawalbeh et al., 2021). Other by-products include sulfuric acid, hydrogen fluoride, hydrochloride acid and nitric acid (Rathore and Panwar, 2022), which is produced during the fabrication process of PV modules where it requires mining and multiple extraction and purification procedures. For comparison, traditional silicon PV technologies has fewer toxic materials in comparison to thin-film PV modules, where film PV technology requires gallium, selenium, telluride, and indium, which can enhance significant environmental consequences if not managed appropriately.

In addition, a significant amount of chemical substances and solvents are used in different processes of various PV types, including hydrogen, hydrochloric acid, nitric acid, isopropanol, ammonia, and selenium hydride (Rathore and Panwar, 2022). These chemicals are considered carcinogenic, corrosive, flammable, and toxic, where they require appropriate treatments. Approximately 37% of the chemicals and solvents used to clean the wafers and remove impurities during the fabrication process are transported to external treatment facilities. In comparison, 35% of waste is released in the form of acid solutions that are diluted and sent to wastewater treatment facilities, and only 0.8% of the waste is believed to be disposed of directly into surface water (Rathore and Panwar, 2022). This has a significant impact on ecosystem quality where it can pose freshwater and terrestrial acidification (Contreras Lisperguer et al., 2020), freshwater ecotoxicity (Cerchier et al., 2022), and freshwater, marine, and terrestrial eutrophication (Mayer et al., 2021). Hence, to minimize environmental impact and preserve raw material resources, it is essential to recycle PV waste and decommissioned modules. This is especially important as most metals used in PV cell manufacturing are rare (Tawalbeh et al., 2021). Mahmoudi et al. (2020) stated that under full landfill disposal scenario, EoL PV waste can lead up to 17,400 kg 1,4-DCB freshwater ecotoxicity, 6780 kg SO2 eq (kilograms of sulphur dioxide equivalent) terrestrial acidification, and 33 kg P eq freshwater eutrophication (kilograms of phosphate equivalent).

4.6.6. Water usage

Water consumption during the operation of PV systems is not significant, as it is primarily utilized for cooling and cleaning PV panels. The use of re-circulatory cooling water and hybrid cooling schemes can greatly reduce water usage for cooling. Still, these methods deplete more energy than once-through cooling systems (Tawalbeh et al., 2021). Although the water usage for cleaning PV panels increases their efficiency, it raises the overall water usage. Several factors, such as dust characteristics, wind speed, panel orientation, temperature, humidity, and glazing properties, can affect the necessary water quantity and cleaning frequency (Dehra, 2018), which differ in different types and generations of PV systems. For example, floating PV systems do not require water consumption for cooling, as their temperature is reduced by the evaporation of water from the reservoir located behind the panel. However, the fabrication and recycling processes of PV systems involve a significantly greater amount of water usage compared to the operation phase, which primarily involves mineral processing, extraction, purification, and chemical etching (Tawalbeh et al., 2021). The excessive water consumption during the fabrication and recycling of PV systems can deplete water resources in natural ecosystems, leading to droughts and negatively impacting local flora and fauna.

4.6.7. Noise and visual impacts

Macroscopic PV modules can have an adverse impact on the environment in terms of visual pollution (Dehra, 2018). This issue is often raised by local communities, environmental activists, and the public and can disagree the installation of PV projects due to the degree of visual prominence. The extent of the visual impact usually depends on the installation area. It is expected to have a significant negative influence on the landscape, particularly in rural areas where most PV modules are installed (Tawalbeh et al., 2021). The visual pollution caused by PV systems installed in areas with high biological diversity and recreational value may face disapproval from the public (Pimentel Da Silva and Branco, 2018). On the other hand, visual intrusion caused by industrial structures is also a major concern for tourist areas, as tourists seek to enjoy nature without any disturbances caused by human activities (Tawalbeh et al., 2021).

5. Limitations and future research

Although the selected studies cover a vast majority of countries globally (as shown in Fig. 4), this review's exclusion of non-English studies constitutes a glaring limitation, severely undermining the breadth and depth of its findings. By neglecting research from diverse linguistic backgrounds, particularly from regions such as China, where cutting-edge PV technologies thrive (al Irsyad et al., 2019), the review fails to capture crucial insights into the global trajectory of PV development. This oversight not only skews the representation of global trends but also overlooks potential impacts unique to specific regions, impeding a comprehensive understanding of the field.

Moreover, while the review acknowledges the pivotal role of policies in transitioning from landfill disposal to recycling for end-of-life (EoL) PV treatment, it falls short in scrutinizing the underlying motivations behind these policies. Without such analysis, the effectiveness and sustainability of these regulatory frameworks remain dubious, hindering genuine progress towards green innovation. Merely relying on Life Cycle Assessment (LCA) methodologies to evaluate recycling processes is insufficient, as it fails to provide nuanced insights necessary for devising robust solutions to systemic issues plaguing the PV industry.

This critical gap underscores the urgent need to explore alternative methodologies, such as system dynamics, to better comprehend the complexities inherent in PV technologies and their lifecycle management. Furthermore, the scant implementation of PV-related regulations in various regions underscores a glaring deficiency in the global regulatory landscape. Future research must prioritize the establishment of robust regulatory frameworks to effectively address PV waste management challenges and mitigate their environmental impacts. Failure to do so risks perpetuating unsustainable practices and undermining the potential of PV technologies to drive genuine environmental innovation.

6. Conclusion

Although PV module has an expected lifespan of more than 25 years the increasing production of these modules suggests that disposing of PV systems will undoubtedly become a significant concern. As PV technologies are expected to play a significant role in decarbonization and the transition to renewable energy, this study confirms that the EoL management of PV technologies must be thoroughly investigated due to the potential adverse environmental impacts. This study revealed that various stages in the life cycle of PV technologies, including the EoL phase, have significantly contributed to different environmental impacts, depending on the specific impact being considered. Previous studies utilizing LCA have effectively identified and quantified the impacts associated with PV technologies, including both qualitative and quantitative analysis. However, these studies primarily focus on highlighting the problem, without delving into potential solutions or exploring the further development of other influential factors.

Despite the pressing need to address the significant environmental impacts caused by PV waste, there is currently limited action in this area, underscoring the necessity for greater attention. Regarding the EoL phase, it is worth noting that while there is substantial knowledge about the potential impacts related to EoL PV technologies, the European Union, and Australia are currently the only regions that have specific regulations in place regarding PV waste or policies that address the integration of methods to effectively mitigate the unintended environmental consequences throughout the various life cycle stages of PV technologies. On the other hand, China, as the leader of the PV market has yet to develop and implement specific regulations to govern the EoL treatment of PV waste. The implementation of policies and regulations it vital where it will enhance the recycling alternative and reduce the level of disposal through financial incentives or simply restriction on the level of landfill disposal. With the implementation of relevant polices, stakeholders are then legally obligated to recycle their EoL PV modules, which will significantly increase the recycling of modules, reduce EoL PV waste and environmental implications associated with landfill disposal.

This review provides a comprehensive understanding of the challenges associated with PV technologies and emphasises the key areas of concern that policy decision-makers and authorities should prioritize. It underscores the need for further research and policy formulation efforts to address the identified issues effectively. The EoL phase of PVs is primarily responsible for the considerable impact across its life cycle stages. Thus, it serves as the ideal commencement for implementing changes and improvements, which can subsequently be extended to the other stages in the life cycle.

To address this issue, a viable solution could be to integrate circular economy (CE) and life cycle assessment (LCA) with system dynamics (SD), which can not only minimize potential impacts and maximize resource efficiency but also aid in policy decision-making and foster green innovations. Previous studies involving PV technologies, utilizing LCA, have already revealed the environmental impacts associated with PV technologies, where the most significant impacts are attributed to the EoL stage, primarily due to the landfill disposal of EoL PV waste. To address this issue within the EoL phase, the concept of a circular economy should be integrated into the product life cycle framework of PV technologies. This approach involves recycling components, promoting the second-life application of materials, and establishing a closed-loop supply chain. System dynamics modelling can then be used to present the results, offering a visual representation through the creation of a causal loop diagram. Furthermore, it enables an in-depth analysis of the environmental impacts using a stock and flow diagram, incorporating quantitative inputs to provide a comprehensive understanding for stakeholders.

By acknowledging these challenges and investing in appropriate solutions, policymakers and authorities can contribute to the sustainable development and widespread adoption of PV technologies. This issue demands immediate attention and effective solutions to ensure the proper management of the substantial upcoming PV waste and prevent further additional repercussions.

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CRediT authorship contribution statement

Ka Hei Kwok: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Paulo Savaget:** Writing – review & editing, Conceptualization. **Shinichi Fukushige:** Writing – review & editing, Funding acquisition. **Anthony Halog:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A1

Abbreviations

PV	Photovoltaic
LCA	Life Cycle Assessment
EoL	End-of-life
CE	Circular Economy
ST	System Thinking
SD	Systems Dynamics
CLD	Causal Loop Diagram
PRISMA	Systematic Reviews and Meta-Analyses

Appendix A2

Table 3
Content Analysis Framework

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
1	Comparative assessment of solar photovoltaic panels based on metal-derived hazardous waste, resource	Y. Y. Bang; N. J. Hong; D. Sung Lee; S. R. Lim	2018	International Journal of Green Energy		X		X	X	X	

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	depletion, and toxicity potentials										
2	Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules	M. M. Lunardi; J. P. Alvarez-Gaitan; J. I. Bilbao; R. Corkish	2018	Applied Sciences-Basel		X		X		X	X
3	Integration & assessment of recycling into c-Si photovoltaic module's life cycle	A. V. Ilias; R. G. Meletios; K. A. Yiannis; B. Nikolaos	2018	International Journal of Sustainable Engineering		X		X			
4	Life cycle assessment of photovoltaic manufacturing consortium (PVMC) copper indium gallium (di)selenide (CIGS) modules	S. Amarakoon; C. Vallet; M. A. Curran; P. Haldar; D. Metacarpa; D. Fobare; J. Bell	2018	International Journal of Life Cycle Assessment		X				X	
5	A Multi-objective Framework for Assessment of Recycling Strategies for Photovoltaic Modules based on Life Cycle Assessment	J. R. Perez-Gallardo; C. Azzaro-Pantel; S. Astier	2018	Waste and Biomass Valorisation		X					
6	Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review	N. A. Ludin; N. I. Mustafa; M. M. Hanafiah; M. A. Ibrahim; M. Asri Mat Teridi; S. Sepeai; A. Zaharim; K. Sopian	2018	Renewable and Sustainable Energy Reviews		X					
7	Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life	F. Corcelli; M. Ripa; E. Leccisi; V. Cigolotti; V. Fiandra; G. Graditi; L. Sannino; M. Tammaro; S. Ulgiati	2018	Ecological Indicators		X		X		X	X
8	Drivers, barriers, and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review	H. K. Salim; R. A. Stewart; O. Sahin; M. Dudley	2019	Journal of Cleaner Production	X						X
9	Ecological network analysis of solar photovoltaic power generation systems	E. Briese; K. Piezer; I. Celik; D. Apul	2019	Journal of Cleaner Production		X				X	
10	End-of-life management of solar photovoltaic and battery energy storage systems: A stakeholder survey in Australia	H. K. Salim; R. A. Stewart; O. Sahin; M. Dudley	2019	Resources, Conservation and Recycling	X			X		X	X
11	Environmental and economic evaluation of solar panel wastes recycling	C. Gonen; E. Kaplanoglu	2019	Waste Management & Research				X	X		
12	The environmental and economic impacts of photovoltaic waste	C. C. Faircloth; K. H. Wagner; K. E. Woodward; P.	2019	Resources, Conservation and Recycling		X				X	X

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	management in Thailand	Rakkwamsuk; S. H. Gheewala									
13	Life cycle assessment for photovoltaic integrated shading system with different end of life phases	M. M. Fouad; A. G. ElSayed; L. A. Shihata; H. A. Kandil; E. I. Morgan	2019	International Journal of Sustainable Energy		X		X		X	
14	Photovoltaic waste assessment of major photovoltaic installations in the United States of America	A. Dominguez; R. Geyer	2019	Renewable Energy				X			
15	Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia	S. Mahmoudi; N. Huda; M. Behnia	2019	Resources, Conservation and Recycling	X						
16	Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling	F. Ardente; C. E. L. Latunussa; G. A. Blengini	2019	Waste Management		X					
17	The balance between efficiency, stability, and environmental impacts in perovskite solar cells: a review	A. Urbina	2020	Journal of Physics-Energy		X		X		X	
18	Eco-Energetical Life Cycle Assessment of Materials and Components of Photovoltaic Power Plant	I. Piasecka; P. Baldowska-Witos; K. Piotrowska; A. Tomporowski	2020	Energies		X		X		X	
19	Economics and impact of recycling solar waste materials on the environment and health care	S. K. Venkatachary; R. Samikannu; S. Murugesan; N. R. Dasari; R. U. Subramaniyam	2020	Environmental Technology & Innovation				X	X	X	
20	Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios	R. Contreras Lisperguer; E. Muñoz Cerón; J. de la Casa Higueras; R. D. Martín	2020	Sustainable Production and Consumption	X	X		X	X	X	X
21	Environmental impacts and economic feasibility of end of life photovoltaic panels in Australia: A comprehensive assessment	S. Mahmoudi; N. Huda; M. Behnia	2020	Journal of Cleaner Production		X		X	X	X	X
22	Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels	T. Maani; I. Celik; M. J. Heben; R. J. Ellingson; D. Apul	2020	Science of the Total Environment		X		X		X	
23	Influence of waste management on the environmental footprint of electricity produced	S. Herceg; S. P. Bautista; K. A. Weiβ	2020	Energies		X		X		X	

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	by photovoltaic systems										
24	Potential environmental risk of solar cells: Current knowledge and future challenges	J. I. Kwak; S.-H. Nam; L. Kim; Y.-J. An	2020	Journal of Hazardous Materials		X		X		X	
25	Private and Externality Costs and Benefits of Recycling Crystalline Silicon (c-Si) Photovoltaic Panels	E. Markert; I. Celik; D. Apul	2020	Energies		X		X		X	
26	Research and development priorities for silicon photovoltaic module recycling to support a circular economy	G. A. Heath; T. J. Silverman; M. Kempe; M. Deceglie; D. Ravikumar; T. Remo; H. Cui; P. Sinha; C. Libby; S. Shaw; K. Komoto; K. Wambach; E. Butler; T. Barnes; A. Wade	2020	Nature Energy	X						
27	Systems approach to end-of-life management of residential photovoltaic panels and battery energy storage system in Australia	H. K. Salim; R. A. Stewart; O. Sahin; M. Dudley	2020	Renewable and Sustainable Energy Reviews	X		X	X	X	X	X
28	Understanding the possibility of material release from end-of-life solar modules: A study based on literature review and survey analysis	P. Nain; A. Kumar	2020	Renewable Energy				X	X	X	X
29	The use of recycled semiconductor material in crystalline silicon photovoltaic modules production - A life cycle assessment of environmental impacts	E. Klugmann-Radziemska; A. Kuczynska-Lazewska	2020	Solar Energy Materials and Solar Cells		X		X		X	
30	Comparative analysis of I2-KI and HNO3 leaching in a life cycle perspective: Towards sustainable recycling of end-of-life c-Si PV panel	J. Chung; B. Seo; J. Lee; J. Y. Kim	2021	Journal of Hazardous Materials		X		X	X	X	X
31	Eco-design for dye solar cells: From hazardous waste to profitable recovery	K. Miettunen; A. Santasalo-Aarnio	2021	Journal of Cleaner Production	X	X		X			
32	Ecodesign of ground-mounted photovoltaic power plants: Economic and environmental multi-objective optimization	M. J. Mayer; A. Szilágyi; G. Gróf	2021	Journal of Cleaner Production		X				X	

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
33	End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy	A. Gautam; R. Shankar; P. Vrat	2021	Sustainable Production and Consumption		X					X
34	Environmental impacts of solar energy systems: A review	M. K. H. Rabaia; M. A. Abdelkareem; E. T. Sayed; K. Elsaid; K. J. Chae; T. Wilberforce; A. G. Olabi	2021	Science of the Total Environment		X		X		X	
35	Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook	M. Tawalbeh; A. Al-Othman; F. Kafiah; E. Abdelsalam; F. Almomani; M. Alkasrawi	2021	Science of The Total Environment		X		X		X	
36	Lead or no lead? Availability, toxicity, sustainability, and environmental impact of lead-free perovskite solar cells	G. Schileo; G. Grancini	2021	Journal of Materials Chemistry C		X					
37	Life cycle assessment for a grid-connected multi-crystalline silicon photovoltaic system of 3 kWp: A case study for Mexico	E. Santoyo-Castelazo; K. Solano-Olivares; E. Martinez; E. O. Garcia; E. Santoyo	2021	Journal of Cleaner Production		X			X	X	
38	A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	G. Ansanelli; G. Fiorentino; M. Tammaro; A. Zucaro	2021	Applied Energy		X		X		X	X
39	Life Cycle Assessment of Coated-Glass Recovery from Perovskite Solar Cells	G. Rodriguez-Garcia; E. Aydin; S. De Wolf; B. Carlson; J. Kellar; I. Celik	2021	Acs Sustainable Chemistry & Engineering		X		X	X		
40	Life cycle assessment of recycling strategies for perovskite photovoltaic modules	X. Tian; S. D. Stranks; F. You	2021	Nature Sustainability		X		X			
41	Life cycle assessment on PERC solar modules	X. Jia; C. Zhou; Y. Tang; W. Wang	2021	Solar Energy Materials and Solar Cells		X		X		X	
42	Overview of global status and challenges for end-of-life crystalline silicon photovoltaic panels: A focus on environmental impacts	B. Seo; J. Y. Kim; J. Chung	2021	Waste Management		X				X	X
43	Recycling and recovery of perovskite solar cells	F.-W. Liu; G. Biesold; M. Zhang; R. Lawless; J.-P. Correa-Baena; Y.-L. Chueh; Z. Lin	2021	Materials Today		X		X		X	
44	The resources, exergetic and environmental footprint of the	N. J. Bartie; Y. L. Cobos-Becerra; M. Frohling; R.	2021	Resources Conservation and Recycling	X			X		X	

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	silicon photovoltaic circular economy: Assessment and opportunities	Schlatmann; M. A. Reuter									
45	Review of State of the Art Recycling Methods in the Context of Dye Sensitized Solar Cells	F. Schoden; M. Dotter; D. Knefelkamp; T. Blachowicz; E. S. Hellkamp	2021	Energies	X	X		X			
46	A scientometric review of trends in solar photovoltaic waste management research	D. Oteng; J. Zuo; E. Sharifi	2021	Solar Energy	X			X	X		X
47	Third generation of photovoltaic panels: A life cycle assessment	M. Krebs-Moberg; M. Pitz; T. L. Dorsette; S. H. Gheewala	2021	Renewable Energy		X		X		X	
48	Comparison of Environmental Impact Assessment Methods in the Assembly and Operation of Photovoltaic Power Plants: A Systematic Review in the Castilla—La Mancha Region	M. Zarzavilla; A. Quintero; M. A. Abellán; F. L. Serrano; M. C. Austin; N. Tejedor-Flores	2022	Energies		X				X	
49	Current situation analysis of solar PV waste management in India	M. Sheoran; P. Kumar; S. Sharma; M. Bukya	2022	Materials Today: Proceedings	X				X		
50	The dilemma in energy transition in Malaysia: A comparative life cycle assessment of large scale solar and biodiesel production from palm oil	Z. X. Phuang; Z. Lin; P. Y. Liew; M. M. Hanafiah; K. S. Woon	2022	Journal of Cleaner Production		X		X	X	X	
51	Does recycling solar panels make this renewable resource sustainable? Evidence supported by environmental, economic, and social dimensions	H.-L. Daniela-Abigail; R. Tariq; A. E. Mekaoui; A. Bassam; M. Vega De Lille; L. J Ricalde; I. Riech	2022	Sustainable Cities and Society		X		X		X	
52	Dynamic material flow analysis of silicon photovoltaic modules to support a circular economy transition	S. A. Khalifa; B. V. Mastrorocco; D. D. Au; S. Ovaitt; T. M. Barnes; A. C. Carpenter; J. B. Baxter	2022	Progress in Photovoltaics: Research and Applications	X	X			X		
53	End-of-Life Photovoltaic Modules	J. Tan; S. Y. Jia; S. Ramakrishna	2022	Energies	X	X		X			X
54	Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules	M. S. W. Lim; D. He; J. S. M. Tiong; S. Hanson; T. C.-K. Yang; T. J. Tiong; G.-T. Pan; S. Chong	2022	Journal of Cleaner Production		X		X		X	X
55	An expert-based evaluation on end-of-life solar photovoltaic management: An	D. Oteng; J. Zuo; E. Sharifi	2022	Sustainable Horizons	X				X		X

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Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	application of Fuzzy Delphi Technique										
56	Global Challenges and Prospects of Photovoltaic Materials Disposal and Recycling: A Comprehensive Review	H. F. Yu; M. Hasanuzzaman; N. Abd Rahim; N. Amin; N. N. Adzman	2022	Sustainability	X			X			
57	Investigating the Remanufacturing Potential of Dye-Sensitized Solar Cells	F. Schoden; J. Detzmeier; A. K. Schnatmann; T. Blachowicz; E. Schwenzfeier-Hellkamp	2022	Sustainability	X						
58	Life Cycle Assessment and Circular Economy: A Case Study of a Photovoltaic Solar Panel in Brazil	M. M. C. Maceno; T. L. Pilz; D. R. Oliveira	2022	Journal of Environmental Accounting and Management	X	X		X			
59	Life cycle assessment and circularity evaluation of a PV panel integrated with phase change material	D. Colarossi; E. Tagliolini; A. Amato; P. Principi	2022	Renewable Energy	X	X		X	X		
60	A multi-country simulation-based study for end-of-life solar PV panel destination estimations	R. Marcuzzo; W. C. de Araujo; M. U. Maldonado; C. R. Vaz	2022	Sustainable Production and Consumption	X		X	X			X
61	Recent progress in silicon photovoltaic module recycling processes	R. Deng; Y. Zhuo; Y. Shen	2022	Resources, Conservation and Recycling		X		X		X	
62	Recent progress towards photovoltaics? circular economy	M. K. H. Rabaia; C. Semeraro; A. G. Olabi	2022	Journal of Cleaner Production	X	X		X	X	X	
63	Recycling of Discarded Photovoltaic Solar Modules for Metal Recovery: A Review and Outlook for the Future	R. Gahlot; S. Mir; N. Dhawan	2022	Energy & Fuels	X	X				X	
64	A review of end-of-life crystalline silicon solar photovoltaic panel recycling technology	X. Wang; X. Tian; X. Chen; L. Ren; C. Geng	2022	Solar Energy Materials and Solar Cells		X		X			X
65	Silicon-PV panels recycling: technologies and perspectives	P. Cerchier; M. Dabalà; L. Pezzato; M. Tammaro; A. Zucaro; G. Fiorentino; G. Ansanelli; K. Brunelli	2022	Metallurgia Italiana		X				X	
66	Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context	N. Rathore; N. L. Panwar	2022	Waste Management & Research		X		X	X	X	
67	Sustainability of photovoltaic technologies in	A. Urbina	2022	Progress in Photovoltaics: Research and Applications		X					

(*continued on next page*)

Table 3 (*continued*)

#ID	Title	Author(s)	Year of Publication	Journal	Circular Economy	LCA	System Dynamics	Recycle	Waste Management	Environmental impact/ Toxicity	End-of-Life (EOL)
	future net-zero emissions scenarios										
68	Anticipatory life cycle analysis framework for sustainable management of end-of-life crystalline silicon photovoltaic panels	Ganesan, K.; Valderrama, C.	2022	Energy	X	X					X
69	Combining circularity and environmental metrics to assess material flows of PV silicon	A. R. Zubas; M. Fischer; E. Gervais; S. Herceg; S. Nold	2023	EPJ Photovoltaics	X	X					
70	Eco-design for perovskite solar cells to address future waste challenges and recover valuable materials	E. S. Akulenko; M. Hadadian; A. Santasalo-Aarnio; K. Miettunen	2023	Heliyon	X			X			
71	Recycling of photovoltaic modules for recovery and repurposing of materials	H. Trivedi; A. Meshram; R. Gupta	2023	Journal of Environmental Chemical Engineering	X	X					
72	Review on recycling of solar modules/ panels	A. Divya; T. Adish; P. Kaustubh; P. S. Zade	2023	Solar Energy Materials and Solar Cells	X	X			X	X	

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