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Systematic Review

Solar Photovoltaics Value Chain and End-of-Life Management Practices: A Systematic Literature Review

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Abstract: Many challenges emerge in the life cycle of solar photovoltaic (PV) panels throughout the processes of their deployment and use in residential, commercial, industrial and transportation sectors. There is a growing need for total product recovery by recycling and reusing the solar panel base and other components in a way that is economically efficient and environmentally sound. This study highlights the urgency to develop and implement a suitable system for the collection and management of photovoltaic systems at their end-of-life cycle and the need for professional implementation of circular strategies in the solar PV value chain. To achieve this goal, a systematic literature review of 81 peer-reviewed articles, published in English between 2013 and 2023, was conducted. The main purpose of the analysis is to examine the value chain of the solar panels covering the period of design, construction, use, end of life, recovery or landfill. The two processes that are investigated include the extent of end-of-life management of PV panels and the extent of circular strategies to reach a sustainable and comprehensive business model. It is argued that the current obstacles faced by solar energy businesses create new opportunities and challenges for innovation within a circular PV industry, and appropriate policies and trained professionals are needed for the implementation of the Sustainable Development Goals (SDGs), including SDG12, in the solar PV value chain.

Keywords: solar PV; economic efficiently; circular PV industry; PV reuse; PV recycling; sustainability

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1. Introduction

Photovoltaic (PV) technology is the direct use of solar radiation to generate clean, efficient, safe and reliable renewable energy [1]. In reliable and suitable climates, manufactured PV panels with capacities ranging from kilowatts to megawatts have been installed for domestic and commercial purposes [2]. It has been projected that by 2050 the installed global PV capacity will rise to 5000 GW [3]. With the average lifetime of panels extending to 25 years, the global solar waste is estimated to be as high as 15 percent of the generation capacity by 2030 [2].

Decommissioned end-of-life solar panels have many environmental, health and economic ramifications that need to be understood in order to avoid creating unsurmountable problems. Researchers have already started to look at these impacts, and examples of areas and studies include the following:

- waste management practices [4,5];
- human health [6,7];
- the natural environment [4,8,9];
- water sources specifically [7];

- economic performance [2,10].

Australia has been quickly adopting solar energy, leading to many opportunities for further developing [11] and deploying PV technology. For example, the northern region of the country, representing 53% of Australia's land mass [12], has both the climate and the space to facilitate large-scale development of solar farms, and planning projects are being discussed to deploy large solar PV capacities. Irrespective of the outcome from the decision on a particular industrial project, Australian households have been the fastest in the world to adopt rooftop solar PV [13]. However, the solar energy industry in Australia, as in most other parts of the world, must address end-of-life cycle management, which currently is left unresolved.

Not only is PV waste already accumulating across the globe but will also continue to do so [14,15], with estimates of 1.7 to 8 million tonnes of waste by 2030 and 60 to 78 million tonnes by 2050 [16–18]. More recent estimates project the volume of solar panel waste to reach 3 billion tonnes by 2050 if no adequate management is put in place [19]. If not adequately recovered and recycled at the end of the operational life of panels, waste associated with precious metal elements such as tellurium, selenium, copper, silver, lead, chromium, silicon and cadmium [20] could be harmful for the environment and human health [21].

The life cycle process of solar PVs includes the extraction and processing of raw materials, the manufacture and transport of PV components; the manufacture of the balance of system components, installation and operation of the PV system and the process of decommissioning and disposing of or recycling of PV components at the end of their operational life [11,22]. For a variety of reasons, ranging from economic to technical and environmental, there is value in considering strategies for recycling, reusing or repairing products and components [23] before solar panels reach their technical lifetime of approximately 25 to 30 years [3,24]. At the end of their life, many installed solar systems will need to be properly managed to avoid creating piles of waste.

It is recognised that circular business models (CBMs) have the potential to encourage smart component design, resource efficiency, the reuse of products and value capture from waste [25]. However, the product services system model should be carefully designed to improve circularity or sustainability outcomes and achieve end-of-life reuse, repair or recycling effectiveness and efficiency [26].

A current conundrum is that a research focus on the design and manufacture of recyclable PV panels that achieve high operational efficiency and performance has had the effect of making efforts into the recovery or reuse of older PV panels expensive and complex [18,27]. A lack of investigation into how CBMs can strengthen the construction and design phases of PV panels and enhance end-of-life recovery or reuse could have negative consequences for consumers and the environment.

Solar PV systems are helping in the transition from fossil fuel-based to renewable energy sources. A multi-level perspective argues that any technological transition needs major changes in a sociotechnical system over periods of time to achieve stability through strong linkages that are supported by co-evolving policies, technology networks, market infrastructures, user practices and cultural meaning [28]. Sustainability transition is no exemption, and a shift to renewable energy plays a major role in this. During the period of replacement of old technologies and the establishing of the new policy, in terms of the technological and economic environment required for solar energy to supersede or replace fossil fuel-based technology, the sector is navigating its way to support the sustainability transition.

Researchers are also looking for answers, with many studies published. Systematic literature reviews of published articles are a good way to capture the latest developments, and in relation to solar PV panels they have covered a technical focus on: advances in solar PV technologies, repairing end-of-life PV panels, energy loss and degradation of PV modules, data forecasting of solar PV production, digital technologies for PV monitoring, recycling and leaching of metal from end-of-life PV waste, determining the basic principles for circular business in the production and reuse of solar cells, market orientation, the necessity of government interventions in PV diffusion and the installation of PV systems by residential households [2]. For example, keywords for identifying published papers relating to solar PV panels and the management of PV waste have included the following: "treatment" or "waste" or "end-of-life" or "recover ∗", "reus ∗" or "recycle" and "PV panels" or "photovoltaic cells" or "photovoltaic" or "solar panels" [29].

To avoid the problems associated with solar PV systems contributing to the accumulation of waste, it is necessary to conduct comprehensive life cycle assessments to understand their environmental impacts [30]. Such an assessment would include the definition of a study goal and scope, inventory, analysis and interpretation of the impacts [31]. Often the production information from currently operating PV systems omits the life cycle details and the environmental implications that are likely to have an effect on the operation of the solar panels and the production of electricity from these systems. Paradoxically, one of the influential factors for the expansion of PV systems as a clean energy source is their environmental performance, including a reduction in greenhouse gas emissions. For instance, in regions where there are periods of snowfall, electricity production from PV panels may be very small, even if there is some sunshine, or high-efficiency PV panels are installed, challenging the use of recyclable systems [31].

There is a great preference to identify and employ economic and better ways for CBMs to regulate and manage end-of-life solar panel waste [32]. While solar panel technologies are continuously being improved, with more efficient systems developed, the management of PV waste remains a challenge. Table 1 summarises the themes related to PV waste management practices. The four emerging themes, as identified by Oteng et al. [1,29], relate to policies and regulations, monitoring, tracking and logistics, infrastructure and treatment pathways. None of them explicitly targets the business models used for deploying the solar PV systems.

Table 1. Themes on PV waste management practices in CBM.

	Themes			
Solar Technology	**Policies and Regulations**	**Monitoring, Tracking and Logistics**	**Infrastructure**	**Treatment Pathways**
First generation	Policies and regulations in place	Collection, monitoring and tracking	Optimised recovery and recycling	Recycling and recovery
Second generation	No policies and regulations in place	No monitoring and tracking	Current/available infrastructure	Landfilling and disposal
Third generation			No infrastructure	Exportation (interstate and overseas)
				Reuse or reconditioning
				Incineration

Source: Compiled from [1,29].

After introducing the development of photovoltaic technology from the perspective of four generations, the paper explains the methodology of the study based on a systematic literature review of business models for deploying solar systems. The results from the review are then presented, including the distribution of the papers and discussion of issues related to circularity aspects. Future research directions and a link to the Sustainable Development Goals (SDGs) conclude the paper.

2. Generations of Photovoltaic Technology

The development of the photovoltaic technology of solar cells can be tracked across four generations [33]. Covering the period from when the first practical solar cell was invented in 1954 to the 1990s, the first generation refers to the early developments and commercialization. Conventional silicon cells made of monocrystalline and polycrystalline silicon and gallium arsenide (GaAs) were the basis of photovoltaic technologies [34]. Silicon was extensively used commercially, and GaAs is the oldest material used for solar cells because of its high efficiency [35].

Second generation refers to the period from the 1990s to the early 21st century, during which a broad category of solar technologies was developed, including thin-film photovoltaic cell technology from microcrystalline silicon (μc-Si) and amorphous silicon (a-Si), copper indium gallium selenide (CIGS) and cadmium telluride/cadmium sulphide (CdTe/CdS) photovoltaic cells [33]. The focus was on cost minimisation [35].

Third generation solar technology refers to current developments in the 21st century and onward, as researchers improve and commercialize advances to increase efficiency, further reduce costs and, increasingly, find innovative ways to apply solar technologies to expanded ranges of industry and consumer uses, including large-scale implementation [36]. More recent chemical compounds, nanocrystalline films, quantum dots, dye-sensitized solar cells, perovskite cells and solar cells based on organic polymers are used, among others [37].

With continuous rapid technological advances, the fourth-generation solar cells are hypothetical technologies for future development. These include low-flexibility or low-cost thin-film polymers [33]. Other anticipated developments are inorganic nanostructures (e.g., metal oxides and metal nanoparticles) or organic-based nanomaterials (e.g., graphene, carbon nanotubes and graphene derivatives) for quantum dot and nanomaterial-based solar cells [38].

Irrespective of the generation of the solar photovoltaics, a future circular economy for end-of-life practices for PV panels can be achieved only by including waste management considerations in the life cycle of production to business and marketing [16,19,39], and ensuring cooperation between stakeholders [40]. End-of-life PV management is essential for technologically advanced economies as well as for any country where the deployment of solar PV facilities and systems is expanding. Detailed approaches have investigated end-of-life PV management in countries such as Australia [41], Bangladesh [42], Ghana [43], India [32] and the UK [44]. There is also a need for countries to cooperate in circular PV business and waste management. In India, for example, solar PV installations are dependent on imports from other countries [45] making the cost of recovery and recycling at the end of their life uncertain because of different product importation. Better understanding is needed of different systems and processes based on specific geographical conditions; solar panel recovery policies; existing regulations and other measures, implementation practices and commercial recycling technologies.

Strategic management plans at all levels and for all generations of solar photovoltaics should include waste regulations that are clear for all stakeholders in the supply chain and lead towards using CBMs. Such policies or regulations ought to be assessed for strength, vulnerability, convenience, risk factors and practicality [32]. There is need for evidence as to what happens to end-of-life solar panels, including the role of individuals, businesses and governments in ensuring that PV waste does not end up in landfill [43]. Most research into circular solar solutions focuses on the technological aspects of PV recycling and dismantling. In addition, CBM studies are needed to both identify obstacles in the adoption of solar cells as well as solutions or options for reuse and recycling of end-of-life panels that could be built into design and manufacturing processes. Hence, a key aspect in a CBM for PV panels is what strategies and business models can be most effective in different market segments from privately owned houses to non-owner residential arrangements (e.g., social, rental and collective housing) to public sector services (public infrastructure, schools, health and social care) and commercial markets (companies and commercial real estate) [18]. The entire value chain of solar PV systems needs to be taken into account to inform any CBMs. This study conducts a systematic literature review to identify the conceptualisation of circularity along the value chain of PV systems in order to facilitate transitioning to more sustainable business models.

3. Methodology of the Study

The systematic literature review (SLR) methodology is a comprehensive, reproducible and rigorous approach for scanning, identifying and reporting the findings from selected literature [46]. Such a systematic literature review of the solar PV value chain in a circular economy makes it possible to explore current international data related to CBM for solar PV systems, their end-of-life management, and the environmental consequences of end-of-life PV waste globally. Thus, this research aims to identify CBMs for the efficient and economic recycling or reuse of PV cells.

Four phases comprised the SLR, namely formulation of the questions, establishing the studies to be included in the review, evaluating the studies and analysis and reporting of the findings. The first three are explained below and the remainder of the paper is based on the analysis of the findings from the SLR [47].

The three research questions (RQ) that guided this review were as follows:

RQ1: In the value chain, which factor/s hinder the integration of a circular economy principle?

RQ2: What is the visual, functional and temporal role of stakeholders in developing sustainable practices for end-of-life PV panels?

RQ3: How should a country (e.g., Australia) plan for managing future solar PV panel waste and what is the existing policy to deal with the issue?

Table 2 presents the range of the studies covered by the SLR. To ensure the reliability of the database and results, the inclusion and exclusion criteria for the selection of articles were determined using keywords. The range of time for the systematic search procedure was defined as being from 2013 to 2023 to ensure coverage of recently available knowledge concerning circular economy and end-of-life PV management. Scopus and Web of Science were the databases used to identify the most relevant types of articles in the English language published in academic journals [47]. The number of published articles within the past two years has increased, indicating the significance of this field of research.

Table 2. Timeframe, data source, search terms and database used in the systematic literature review.

Timeframe	2013–2023
Data source	Journal articles and conference papers published in English
Search keywords and terms	("solar system" OR "solar PV" OR "rooftop solar") AND ("circular business model" OR "end-of-life" OR "value chain")
Searched database	Scopus, Web of Science

In order to determine whether a paper met the inclusion criteria, the title, abstract and content were scanned (see Figure 1) following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidelines [48] (see Supplementary Materials). The papers irrelevant to the above three questions that guided this review were excluded. This process filtered out many papers and resulted in 81 articles that were then organised according to their findings concerning the following: the risk of end-of-life solar PV e-waste assessment, figures, facts and concerns towards a circular economy and the current technical treatment and analysis of solar PV waste management, recycling and recovery of waste in a structured and integrated solar PV and thermal energy system.

The following section reports some bibliometric information related to the distribution of the selected papers. This is followed by an analysis of the findings related to scenarios for end-of-life PV panels, circular solar PV business models for PV systems and the database that addressed whole-of-life design and resource reuse of solar PV panels in a circular economy.

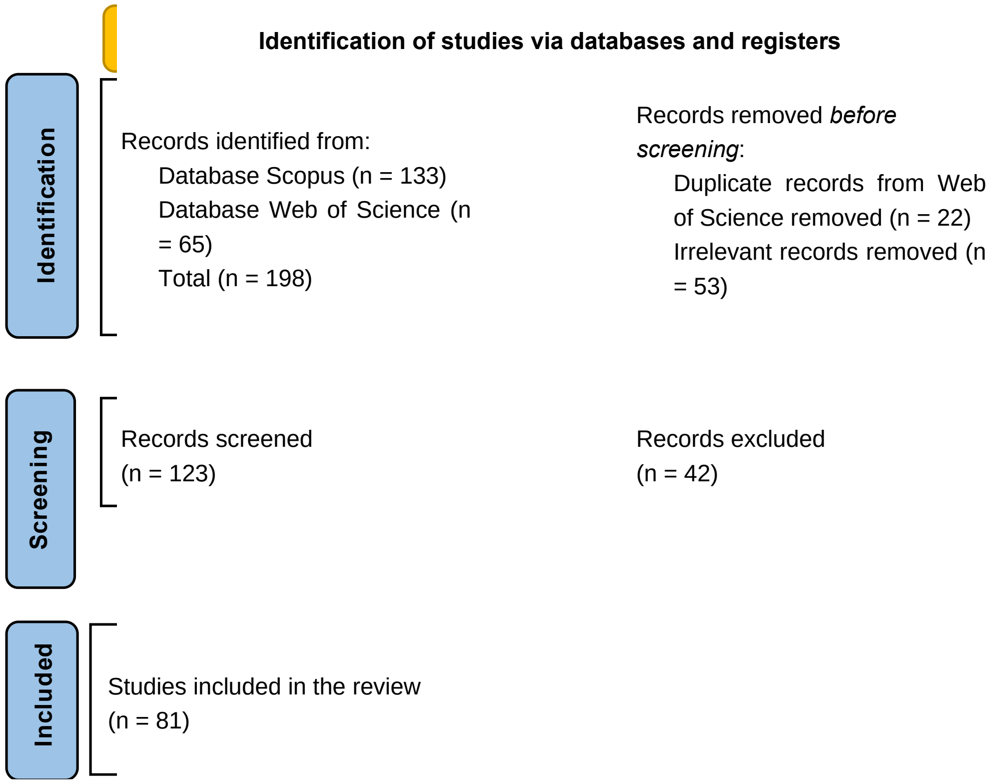

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 flow diagram for this systematic review.

4. Bibliometric Distribution of the Selected Paper

With academic journals constituting the major avenue for disseminating research results in the Scopus database, Figure 2 presents the time distribution of the papers identified during the SLR over the 11-year period analysed. The review found an increase in recent years in the number of papers that addressed PV cells based on a circular economy approach. This reflects the increasing trend for research to focus on the field of PV cells as a renewable energy source compared to other sources, especially since 2013. Around 70 percent of the papers were published since 2020 (Figure 2), with the majority (n = 31; 41%) appearing between 2021 and 2022. The apparent drop in 2023 is due to the year being incomplete at the time of the data collection. This time distribution suggests academic research was undergoing an incubation period before 2013, especially in relation to the analysis of value chain actors and dynamics, and emerged stronger after 2018.

Of the 81 papers analysed, six were published in the journal Sustainability, four in Energy Policy, six other journals published three papers each, followed by three with two papers each and 47 journals with only one paper (see Table 3). The open-access journal Sustainability, established in 2009 and published by the Multidisciplinary Digital Publishing Institute (MDPI), Switzerland, is considered a high-quality outlet ranked highly (Q1) in the area of geography, planning and development [49]. It is not surprising that this particular journal has attracted the most papers as it is multidisciplinary in nature and open-access, allowing for fast publication, and energy is one of the topics it covers. Energy Policy is a similarly highly ranked (Q1) journal with a specific focus on energy, including economic, environmental, social and planning aspects. It is also evident that a range of specialised journals welcomed papers on the topic of the PV value chain and the concept of the circular economy as a new approach to optimise limited resource usage, reduce waste generation and address issues related to the environment and energy.

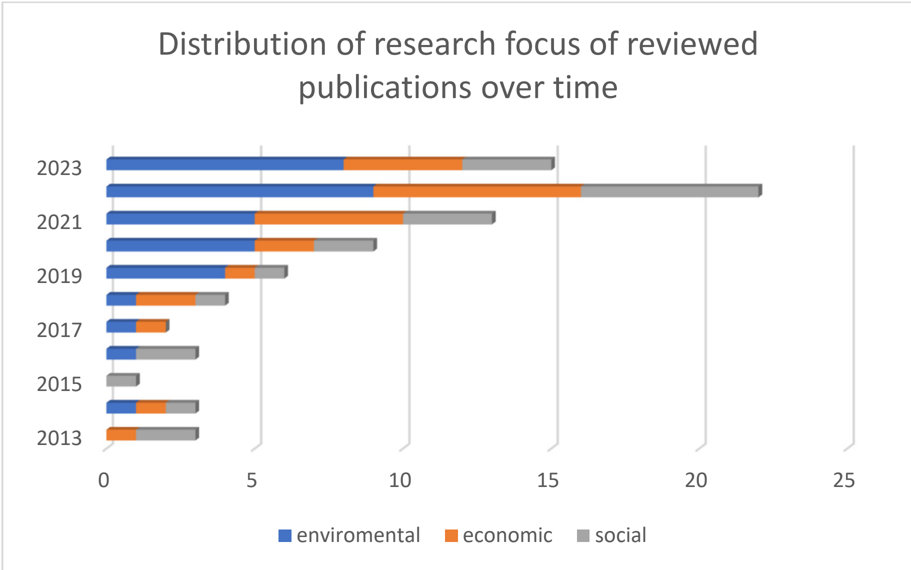

Figure 2. Distribution of reviewed publications over time according to research focus.

Table 3. Distribution of published papers and journals.

Journals	Number of Published Papers per Journal	Total Papers
Sustainability	6	6
Energy Policy	4	4
Energy Conversion and Management; Journal of Cleaner Production; Resources, Conservation and Recycling Advances; Sustainable Production and Consumption; Applied Energy; Renewable and Sustainable Energy Reviews	3	18
Climate Policy; Energies; Energy, Sustainability and Society	2	6
Acta Astronautica; Aerospace; Australian Planner; Clean Technologies and Environmental Policy; Cleaner Engineering and Technology; Computers and Industrial Engineering; Development Policy Review; Energy Nexus; Energy Research and Social Science; Energy Sources, Part B: Economics, Planning and Policy; Environment, Development and Sustainability; Environmental Progress and Sustainable Energy; Environmental Science and Pollution Research; Environmental Technology and Innovation; European Planning Studies; GCB Bioenergy; Heliyon; IEEE Transactions on Power Electronics; Industry and Innovation; Innovation and Development; International Journal of Energy Sector Management; International Journal of Green Economics; International Journal of Scientific and Technology Research; International Journal of Sustainable Energy; Journal of Asian Energy Studies; Journal of Business Research; Journal of Energy in Southern Africa; Journal of Environmental Management; Materials Chemistry and Physics; Materials Today: Proceedings; Metallurgical Research and Technology; Proceedings of the Institution of Civil Engineers: Engineering Sustainability; Renewable Energy; Renewable Energy Focus; Revista de Gestao; Science of the Total Environment; Solar Energy; Solar Energy; Solar Energy Materials and Solar Cells; Solar Energy Materials and Solar Cells; Sustainable Energy Technologies and Assessments; Sustainable Horizons; Sustainable Materials and Technologies; Waste Management; Waste Management and Research; Water, Air, and Soil Pollution; World Development	1	47

Figure 3 shows the distribution of published research by countries that are involved in solar PV cell capacity in various forms. Research in Australia and India resulted in 16 research papers (8 from each country), followed by China (5), the US (4) and African countries and Germany (3 each). One or two papers reported research for the remaining countries (Figure 3).

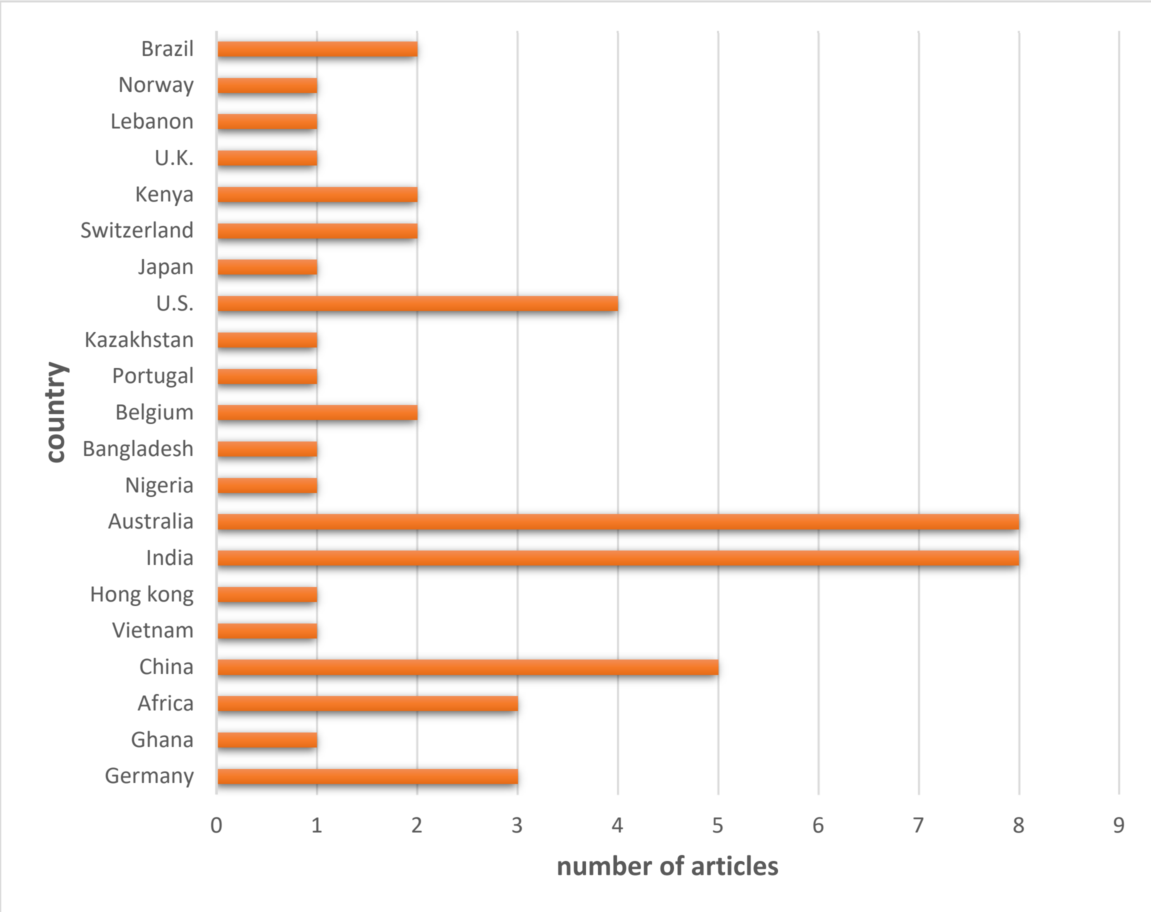

Figure 3. Publications per year by country.

Methodologically, three different approaches to research are present in the 81 papers. They include the following: (1) literature review and assessment of the findings of previously published papers; (2) general conceptualisation and theoretical case studies of data to determine possible frameworks; (3) analysis of theories for circular solar PV business models with the aim of measuring the ratio of circular flow in social, environmental and economic spheres.

Figure 2 shows the distribution of the papers according to their research focus overtime. The majority of the papers (34 or 42%) addressed circularity with an environmental focus; this was followed by articles investigating financial profitability and the costs of PV panels within a circular economy performance (24 or 30%), with the remaining publications covering social issues (23 or 28%). This distribution is relatively balanced given that the main driver behind circularity is the protection of natural resources and the biophysical environment.

The environmental issues covered in the papers were related to cutting greenhouse gas (GHG) emissions, reducing the risk of toxic material in landfill, and overall helping to reduce global warming [1,29]. Furthermore, the economic issues addressed by the papers reviewed relate to cost savings, energy pay-back time reduction, new businesses and reducing the use of raw materials after progressing in a circular economy. The social issues covered included job creation, development of skills and capabilities and reducing the risk to humans caused by toxic substances [16].

The development and adoption of a policy framework for end-of-life analysis would encourage stakeholders and producers to adhere to international standards throughout the supply chain. However, the review suggests an absence of a suitable framework to guide the solar PV panel industry and stakeholders towards the adoption of a CBM and be proactive in responsible energy use and sustainability, as well as the preferred and correct end-of-life disposal of solar PV panels. There is also a need to promote and set up regional training centres to address the process of training experts in solving the problems of reuse, repair and recycling for solar panels. The industry as a whole needs to address a framework for managing end-of-life issues in social, environmental and economic spheres [43]. None of these issues were covered in the identified papers. Nevertheless, the range of other issues covered is quite large and the discussion to follow delves further into them.

5. Thematic Results and Discussion

The value chain of solar PV panels is complex, because of the variety of processes used, different circular strategies and business models employed, sizes of solar farms and installations as well as operating companies and the potentiality of recycled PV wastes. Despite this complexity, stakeholders continue to explore how to switch from fossil-based fuels to renewable energy sources, including solar PV technology. Proper management of projects related to the recovery of solar panels offers social, economic, development and environmental opportunities, which contribute towards the reduction of greenhouse gas emissions.

Table 4 summarizes the SLR articles (n = 81) that relate to different sectors of the solar PV value chain. It starts with raw materials; covers various technological aspects of solar PVs; extends to supply chains, installation processes, job market, business models and costs; relates to government and other institutions, health and environmental concerns, end-of-life and close loop systems and the use of battery storage to improve the reliability of this type of renewable energy and concludes with overall PV system benefits. These themes cover the entire life cycle of the solar PV systems. Although raw materials, cost, job markets and PV system benefits may be seen as being outside the narrow solar PV value chain and end-of-life practices, it is important to also include them as the main aim is a circular economy that provides efficiencies and sustainability opportunities. This helps understand whether circularity reduces the reliance on raw materials and how it impacts on costs and jobs as well as whether there are any improved whole-of-system benefits. Many of the identified articles are allocated to more than one thematic area because of their multidisciplinary nature and breadth of the covered topics. Figure 4 shows the distribution of papers per theme.

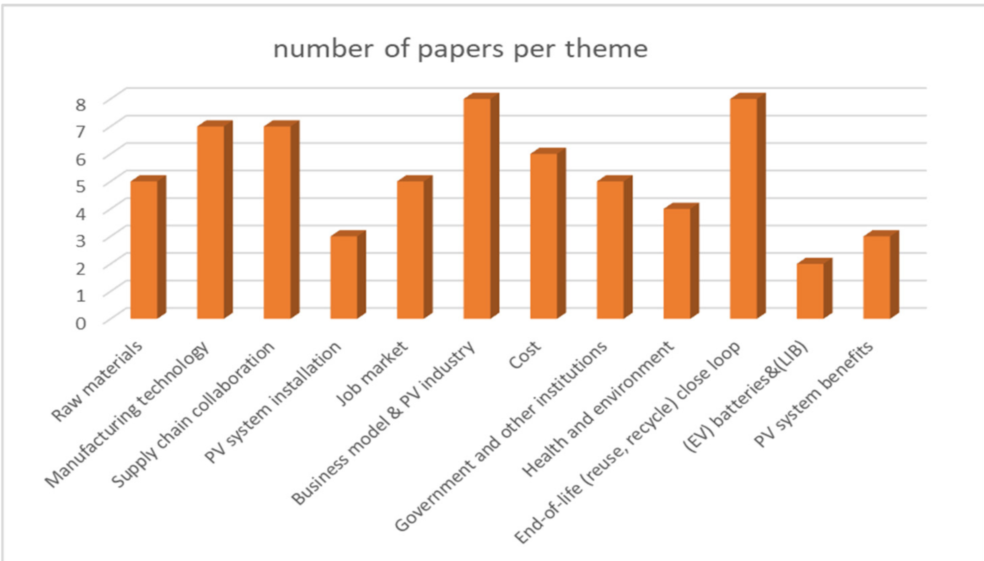

Figure 4. Number of papers per theme.

Table 4. The solar PV value chain.

Category	Description	References
Raw materials	Initial access to knowledge of raw material to manufacturing end-of-life (EOL) panels	[2,33,42,50,51]
Manufacturing technology	Improving solar cells for high efficiency	[20,42,50,52–55]
Supply chain collaboration	Collaboration within the supply chain to access EOL scenarios for PV models	[32,42,52,56–60]
PV system installation	Appropriate framework that helps to create options for dealing with EOL PV panels installation	[18,19,61]
Job market	Job market in the PV industry	[1,11,20,32,42,62,63]
Business model & PV industry	Business models used in the PV industry	[18,20,25,32,64–67]
Cost	Economic viability and low cost of PV panels' end of life	[16,20,42,51,61,68]
Government and other institutions	Government and other institutions policy on formal PV development	[18,20,69,70]
Health and environment	Determining the risk to human health or environment	[1,41,55,68,71]
End-of Life (EOL) close loop (reuse, recycle)	Promotion related to efficient management for EOL solar PV panels	[16,42,44,53,61,68,72,73]
Electric vehicle (EV) batteries Lithium-ion Batteries (LIB)	Benefits of lithium-ion to supplement solar PV system	[73,74]
PV system benefits	Increasing the benefits from the circular economy concept for PV panels	[18,20,75]

5.1. Raw Materials

In relation to the raw materials used, the review results show that circular solar PV business models for end-of-life panels mostly concentrate on new wafer and cell engineering processes used in the manufacturing of silicon and thin-film PV cells. As, among modules, monocrystalline and polycrystalline silicon panels have more conversion skill compared to thin-film panels, they are currently used worldwide, mostly as commercial solar-panel materials [42]. In particular, the cadmium telluride (CdTe) used in solar cells is a semiconductor material with high optical absorption coefficient, and its recovery efficiency is very high [33].

One way to control solar cell waste is to raise awareness about PV panels at their end of life (EOL) among sectors involved with PV energy, including companies, installers and legislators [2]. Determining laws and regulations that take measures to manage and deal with raw materials correctly and safely is essential. Countries such as Kenya face challenges in accessing knowledge about the raw materials in order to localize their solar module production [2,42].

Most of the metallic fraction by weight in the connecting wires of the panels is raw materials such as copper, lead and tin. Present studies are looking for a process to recover metallic copper along with lead and tin without exposure to the environment. For example, toluene solution can be used for copper recovery [51]. As these are essential materials for the construction of panels, planning for their recovery or reuse must be present in the solar cell manufacturing cycle [33].

5.2. Manufacturing Technology

With respect to the manufacturing technologies, opportunities for circularity need to be explored in passing the extended accelerated life cycle protocols in edge seal and encapsulation technology for the CdTe-based solar cells produced by the deposition of four layers, namely transport conductive oxide (TCO), n-type cadmium sulphide (CdS), p-type CdTe and a layer of conducting material. Steel, copper in cables and aluminium frames in the EOL PV panel systems are easily recyclable, which can be undertaken voluntarily by PV manufacturers or third-party services [54]. Specific European regulations play an important role in the recycling of PV panels and electronic waste, and reducing such waste in landfills [42]. In fact, recycling of solar panels leads to cost savings, particularly for the government, and job creation [54].

The reviewed literature reported concerns the scarcity of the base metals that make up the CdTe thin-film cells. Effective ways to minimise the carbon footprint were also suggested. They include fitting water heating systems into solar PVs, developing heating processes and solar desalination applications during manufacturing, and retrofitting already deployed panels. Country-specific perspectives are also presented, such as in Bangladesh [42] and Kenya [50].

Newly emerging concepts for solar power panels are as follows: (1) organic-based PV cells, (2) solar concentrator systems and (3) quantum cells. For recycling EOL silicon-based and thin-film solar PVs, the physically separated components are further separated according to their thermal and chemical elements. Recovered CIGS (Cadmium Indium (Gallium) Selenide), CdTe (Cadmium Telluride), CIS (Cadmium Indium Selenide) and silicon components can be reused in new solar panel systems, even though some are separated as waste [55].

Today, only copper wires are reused out of the whole PV panel and burning of the plastic materials is required, which causes the emission of smoke released into the environment [20]. From an environmental point of view, a significant hotspot due to high electricity consumption is silicon purification during the manufacturing process [52]. Various cooling techniques and solar thermal collectors are suggested to conserve solar energy, converting it to heat with more efficient thermal management systems [53]. In all of these technologies, despite significant and increasing competition from solar PV manufacturers, there must be communication between the upstream and downstream sectors to use a framework to explore potential resources [42,53].

5.3. Supply Chain Collaboration

Regional, national and local stakeholders must be active in PV management to increase PV energy sources and EOL PV management, with government and non-government regulators stressing extended producer responsibility. There are three levels of supply chain cooperation. First is the management of solar panel waste at the initial stages, which should be the norm. Second, initiatives should enhance skills and education to establish the solar waste management drives. Third, approaches for managing solar waste can be adopted for stakeholders at different levels to avoid landfill treatment and procure a green pathway for waste management [32].

There are four main issues in connection with circularity throughout each stage of the PV value chain. First, since the current designs of solar panels are such that they do not allow separation, restoration and recycling after their initial optimal life period, the efficiency of the panels and these key limitations should be considered and improved in the research and design stage of the panels. Second, to develop a suitable business model, all aspects of the panels should be considered, such as cost, primary products, execution and duration of performance and lifetime. Third, from landfill, solar panels can break and release toxic gas and chemicals into the environment. Producers and recyclers ought to be encouraged to coordinate their efforts to reduce toxic substances. Fourth, toxic chemicals and materials such as lead, cadmium and chromium cannot be separated or recovered without removing all parts of a panel. Due to the lack of suitable technology for the recovery of solar panels, many experimental projects are underway to improve the efficiency of the panels along with managing the toxic substances that make up the solar cells [60].

The evaluation of supply chains highlights workers as the stakeholder group with the highest social impacts [56]. A main concern along the supply chain is the environmental impacts of the different PV recycling techniques used in the EOL management [57]. This equally applies to traditional grid-connected and solar stand-alone systems [59]. Another aspect is finding a techno-economic model to determine when it is environmentally worthwhile to recycle for material recovery compared to virgin material use [58]. Localizing PV services allows more attention to be placed on the sustainable industrialization debate; activation of regional, national and local stakeholders; proximity to customers and collaboration in the supply chain to access EOL scenarios for PV models [42].

5.4. PV Installation

Solar PV technology is an increasingly affordable and accessible technology that has mainly benefited households, but not the non-homeowner markets to any great extent. Data should be used to examine non-owner residential markets (including social, rental and collective housing) and public markets (including schools, health and social markets) to create a clear framework that removes obstacles and encourages mechanisms other than energy saving potentials [19,61]. Despite the high price of energy, this is often not a sufficient condition for investment in the PV panels sector; specific regulatory and institutional conditions must apply [18].

With EOL PV installation being a hybrid public–private partnership, synergy between different actors with clear roles is needed [43]. In densely populated countries, such as India, if more than 6% of households install PV panels, EOL management will be a difficult task, with landfill and increased pollution being the likely outcome [61].

5.5. Job Market

Job creation will accompany the growth of circularity in the solar PV industrial sector [32]. Beyond clean electricity generation by PV cells and countering climate change, additional benefits are job creation, improvement of local skills and development of income-generating activities [62]. Investment by national, state and local governments will be attracted if resource security, supply chain stability, job creation and new market opportunities can be generated [1]. Manufacturing, construction, installation and maintenance are potential fields for employing hundreds of thousands of people, which is an important consideration if indications are correct that the conventional electricity industry workforce will decrease [11].

Employment growth in the solar cell technology field complements social concern for renewable energy targets contributed by solar PVs [42,63]. The management of EOL and unwanted solar PV panels helps encourage industry to consider different job opportunities for the recycling of solar PV panels at the point of product design as well as develop environmentally friendly recycling processes and appropriate marketing to counter the increasing global disposal of PV panel waste. A systemic approach is needed to prepare training and employment opportunities for the new skill sets and workplace competencies required for recycling and disposing of solar PV panel waste [20].

5.6. Business Models and PV Industry

Current mechanical, chemical and thermal methods for recycling and reusing EOL solar panels are at the initial stages. Only when circular technology processes become more widespread will CBMs become more viable [32]. The three CBMs for solar PV systems most commonly proposed in the literature are product–service systems, second-life sustainability models and EOL management.

- Product–service system: Under this model, customers have the advantage of a product–service system (PSS) because they can use products or services without purchasing them directly. The PSS bypasses the upfront costs of installation and maintenance costs, encouraging customer adoption and promoting PV circularity [64] through the reuse, repair and refurbishment of products. Schmidt-Costa et al. [64] identified use-oriented and result-oriented PSS alternatives that may overcome obstacles such as initial costs, a lack of financing options and limited access to appropriate installation sites, even in a region with highly favourable conditions for solar PVs, such as California. A use-oriented PSS includes maintenance and repair services in the rental or lease contracts [65]. In a result-oriented PSS, the consumer pays a predetermined fee for the energy generated, usually measured in kWh. Payment is determined by the results or product performance, such as the amount of energy produced by a PV array. Reim et al. [76] identified three structures for PSS models. A product-oriented PSS holds the provider responsible for the products and services, which the customer pays for. In a use-oriented PSS, the provider is responsible for the usability, which the customer pays for over time. A result-oriented PSS has the provider responsible for results and the customer pays for units of outcome. The PSS model has the advantages of increased solar technology affordability and availability, customers have less financial risk and resource efficiency is increased [64]. On the other hand, the PSS model must address key issues such as active stakeholder engagement and communication, clearly defined value propositions and pricing structures, which can be complex.

- Second-life model. Under this model, PV products are repurposed at the end of their original life to reduce waste, save resources and generate economic benefits [66]. In a second-life cycle, components can be integrated for new use into building materials and furniture, or they can be repaired for reuse in solar panels. Bocken et al. [25] propose that solar panel collection systems be combined with product design strategies to facilitate the reuse, refurbishment and recycling of materials and components to create new products. However, effective second-life models have supportive legislation that puts the responsibility onto producers to manage waste and feed it back into second-life processes [20]. Such product stewardship programs also emphasise consumer education about the challenges of waste associated with solar PV panels and encourage demand for second-life products and services [20].
- EOL management. A recycling system to recover materials and components from EOL products is another CBM that can promote circularity in the solar industry. This CBM promotes the creation of new products, a reduction in raw material consumption, and increased resource efficiency. Recycling systems can be designed to recover silver, copper and aluminium from used solar panels [67]. Reduced landfill is another advantage of recycling PV waste.

Product–service systems, second-life sustainability models and EOL management CBMs illustrate the need for significant system rethinking to achieve a circular economy, particularly in product design, alternative business models and, importantly, for investment, because studies show that economic benefits follow investment in the recovery of valuable materials and reduction of waste management costs [25]. There is a complex value chain in the assembly of solar panels/modules, which are then combined with other parts into solar systems. A circular economy creates closed-loop supply chains for materials, components and products to be reused, recycled and refurbished. Economic benefits are assured, as too is the positive environment impact with reduced amounts of hazardous waste and greenhouse gas emissions associated throughout the value chain of the photovoltaic systems [18]. Businesses need to understand how they can avoid the pitfalls associated with waste and transition to circularity yet remain economically viable, generate environmental benefits and provide socially desired renewable energy through their products and services.

Life cycle assessment (LCA) studies could be used to compare the environmental impacts of different CBMs, which would include energy consumption plus greenhouse gas emissions, water usage and waste generation. Social impact assessments could look at potential job creation, skill development and community engagement opportunities that come from different CBMs [77].

5.7. Cost

Inefficient and uneconomic processes not only make any recycling process expensive but also reduce the motivation of manufacturers to cooperate in recycling and reusing PV panels [61]. An economic benchmark for the commercial feasibility of PV panel recycling can be estimated from the value of scrap for materials used in PV panels. Scrap glass has a limited value of only about USD 10 per ton, while the current values per ton are USD 800 for scrap aluminium, USD 1000 for silicon, and USD 5000 for mixed copper [42,61]. Considering that the weight of a 300 W solar PV panel is approximately 20 kg, an optimistic recycling rate of 100 percent suggests a combined value of recyclable materials at current scrap values is approximately USD 4.14 per panel [20]. The total estimated solar waste forecast of 78 million tonnes is expected to provide approximately 0.42 million tonnes of copper from c-Si solar panels by 2050, resulting in a value of USD 4.53 billion as of now [51]. This is a relatively low figure to expect the market to function on its own without any government support.

Recycled raw materials, however, play an effective role in contributing to the circular economy. Empirical estimates show that solar PV installations with advanced recovery capabilities of 2.95 billion tons of e-waste in India can return metals worth USD 645 trillion to the reuse cycle, creating possibilities for a circular economy-based supply chain for the management of e-waste [16].

A cost-benefit analysis would look at the economic benefits of various CBMs, including upfront costs, operating costs, revenues from recovery or second-life sales and cost reduction from waste disposal, among other considerations. Furthermore, a detailed life cycle cost analysis (LCCA) can determine the potential economic benefits of recycling solar PV systems and circular strategies. It should consider factors such as the value of recovered materials (e.g., silicon, silver and aluminium), energy savings from recovery and recycling, avoided costs of waste disposal and potential income from second-life sales or leasing models. The analysis should account for costs associated with collection, transportation, processing and recycling, as well as potential support or incentives for circular economic practices [16].

The cost of the initial solar cell construction projects and their recovery and recycling process after the end of life is exponentially increasing globally [68]. However, some solar module manufacturers, such as those in Kenya, have managed to remain in the market, despite economic challenges [42].

5.8. Government and Other Institutions

Industry stability and clarity would be assured with regulation and collaborative supply chain approaches. Uncertain and evolving government policies and regulatory initiatives affect the market penetration of circular solar PV systems. Governments should encourage innovation but also prevent negative welfare and abuse of market power [18]. Collaborative approaches to deal with PV waste effectively would involve incumbent and start-up firms, government, research institutions and service providers planning a supply chain that relates to all stakeholders [69].

Maqbool et al. [77] argue that governments can introduce a range of incentives and regulations, such as the following:

- Tax credits, subsidies or feed-in tariffs that encourage the adoption of circular economic practices and ensure the useful recycling of economic resources;
- Extended producer responsibility (EPR) policies that can shift the financial burden of EOL management to manufacturers, encouraging them to use and generate recyclable materials by applying circular economic principles;
- Landfill bans or charges for solar PV waste disposal.

All these would create economic incentives for recycling and resource recovery [20,70].

5.9. Health and Environment

In the coming years, the volume of PV waste will increase because of the high uptake of rooftop solar PVs. Photovoltaic energy plays an essential role in reducing GHG and environmental effects by decreasing particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO_2) pollutants. All of them have negative consequences for human health and environmental well-being, and such additional PV waste management facilities require policy support and appropriate environmental and health impact regulations [1,41]. Although the use of solar energy can be beneficial for human health by reducing the production of pollutants, the disposal of used solar panels can create risks for humans and the environment [70]. One such risk is the landfilling of panel waste, which also causes soil pollution. Landfilling of solar panels was estimated to cost AUD 6.8k per MW, compared to the most appropriate and selected on-site option of mulching [68].

A proper life-cycle analysis (LCA) has the capability to evaluate the environmental footprint of solar photovoltaic systems by factoring in greenhouse gas emissions, water consumption, land use and toxic emissions throughout their lifecycle from extraction of materials to system disposal. Comparisons with other energy sources (e.g., fossil fuels, nuclear power or wind turbines) can help the environmental assessment, including the possible effects of the hazardous materials present in solar PV cells, such as cadmium, lead and other components harmful to human health and the environment [78].

While recent trends in solar research are aimed at improving efficiency, limited importance is given to the waste disposal of dismantled solar power panels and its health and environmental effects [55]. This similarly applies to packaging materials and used solar panels, whose volumes are expected to grow. For example, some research has looked at the potential risk to human and environmental health from applying shredded end-of-life packaging materials to surface soils [68]. Environmental assessment of solar PV installations and mitigation measures should be especially undertaken in sensitive or protected natural areas [79].

Strict environmental and safety laws can regulate the manufacturing, transportation and disposal of hazardous materials used in solar PV cells. Alternative materials or technologies should be developed to reduce or eliminate the use of toxic materials. Closed-loop recycling facilities can ensure proper monitoring and storage of any hazardous materials involved in maintaining the end of life of solar PV panels.

5.10. End-of Life (EOF) Closed Loop (Reuse, Recycle)

Minimising the environmental impact of PV waste has some urgency given that PV systems are a key government target for combating global climate change and reducing dependence on fossil fuels [44]. With estimates of 1.7 to 8 million tonnes of waste by 2030 and 60 to 78 million tonnes by 2050 [16–18], waste reduction and recycling EOL products can significantly impact the supply of critical materials [42,53,68,72,73]. Similarly, the emissions of radioactive substances like radon-222 from solar PV production processes, and the disposal of them, impacts water resources and land resource [1,71].

Although different countries, such as the Australian government, have, since 2014, banned PV waste from going to landfill, the extent of PV recovery and recycling is still under investigation [1]. Only a few companies are capable of handling recycling efficiently, and various technical aspects of the solar panel waste recycling, recovery, reuse, environmental protection and waste management should be checked [55].

Efficiency and scalability of any possible solutions are essential. Comparative studies evaluate the efficiency, recovery, energy consumption and environmental impacts of different recycling technologies, such as mechanical, chemical and thermal processes. The scalability and economic viability of recycling technologies are assessed against factors such as capital and operating costs, capacity and market demand for recycled materials. The findings of comparative studies also explore the potential of combining advanced technologies such as robotics, automation and artificial intelligence to make recycling more efficient and cost effective [80].

5.11. EV Batteries/Lithium-Ion Batteries (LIB)

Global energy processes tend to be driven by technical and economic criteria, but they are increasingly being challenged by sustainability strategies related to energy security and climate change. The answer to whether grid-scale lithium-ion batteries can be considered to meet the growing storage needs of the future is not simple because there are other factors that affect the future of storage with a number of interdependencies [74].

Cleaner transportation with EV technologies, and renewable energy, are mitigating solutions. Most electric vehicles utilize LIB, which reach their EOL when their capacity is reduced by 20%. Owners or manufacturers of EVs could recover some costs related to buying or making EVs by selling LIB packages to energy companies for use in electrical storage. Such recycling and reuse of EV batteries can be the basis of an energy strong system but will depend on government policy and the cooperation of the EV market [74]. China has ensured that newly regulated EV makers are responsible for the recovery of batteries by arranging recycling channels and service outlets to collect, store and send old batteries to recycling companies [73].

5.12. PV System Benefits

Most renewable energy countries support EOL treatment and total product recovery with increasing solar energy production. The benefits from using PV systems appear to be well-established, as indicated with their uptake across the globe. Of particular interest is the uptake in the most populous countries as well as in high-income economies. India is one of the top 10 consumers in the PV market. By 2022, India aimed to have 100 GW of solar power capacity installed, including both grid-connected solar power and off-grid solar applications. China has made enormous strides in building up its solar power capacity within the past decade, growing cumulative capacity from only 4.2 GW in 2012 to 392.6 GW in 2022. With an annual growth of 41.4 GW of newly installed capacity in 2022, the growth of the European market was 47% above the previous year, reaching a total installed PV capacity of 208.9 GW. Solar PV expansion in Germany jumped 28% in 2022, with 7.2 GW of new installations added to the grid in 2021. Japan has a major role in the development and research of photovoltaic panels and produced 84.91 GW through solar PV technology in 2022. In the United States (the fourth largest market in photovoltaic energy generation after China, Germany and Japan), the PV market has grown rapidly since the middle of the first decade of this century. In 2022, the United States' cumulative solar photovoltaic capacity amounted to 111.5 GW, an increase of nearly 100 GW compared to 2010. In June, 2019, there were over 2 million solar PV installations in Australia, totalling a capacity of 12.9 GW [20], including more than 290,000 rooftop installations added to the grid, with a total capacity of 2.51 GW in 2022. In all these countries, the need and economic benefits of recycling, recovering and reusing PV panel components are driving consistent efforts to develop strategies to do so [18,75].

6. Sustainability and PV Management

At an upper level, the circular economy concept can be interpreted as a complementary part of sustainable development and touches on a number of United Nations SDGs, with Goal 12, Responsible Consumption and Production, presenting itself as the most pertinent. In focusing on the effective recycling of PV modules, 10 of the 17 SDGs can be deemed relevant. In essence, this signifies that the attainment of sustainability in a PV module recycling system has a multitude of beneficial outcomes on other issues and objectives beyond this particular industry. This could potentially exert an influence or motivate other industries to adopt similar measures, thus enabling the PV industry to set an example [60].

The analysis of the current body of literature covered a broad range of issues and can inform the basic essentials of the solar photovoltaics value chain and EOL management.

It allowed for the three research questions to be answered, and the main insights are summarised below:

- RQ1: In the complex value chain of solar PV systems, there are multiple factors that hinder the integration of a circular economy approach. First are conflicting interests, where manufacturers may place cost effectiveness above environmental sustainability and recyclers favour profitability. Second, there is inadequate supportive legal frameworks or enforcement provisions that ensure compliance with proper waste management and recycling practices. Third, there is the absence of an effective communication or education campaign to enhances stakeholder awareness and knowledge on the benefits of implementing circular economy approaches for solar PV systems.
- RQ2: The role of stakeholders in the development of sustainable practices for end-of-life PV panels is essential, and it should be seen in collaboration and partnerships. There are some excellent examples of collaboration from the EU, and such best cases should be seen as models to be adopted across the world given the identified lack of a suitable framework to guide the CBM for the solar PV panel industry. They include extended producer responsibility (EPR) schemes which encourage manufacturers, importers and recyclers to cooperate, such as the Waste Electrical and Electronic Equipment (WEEE) Directive from the European Union [23] and voluntary take-back and recycling program by the PV CYCLE association in Europe [81]. In Australia, the Circular PV Alliance developed circular economy solutions for solar PV waste management as a collaborative initiative involving industry, government and research organisations [82]. Partnerships are a deeper form of collaboration between governments, manufacturers and recyclers to develop recycling infrastructure and promote circular economy practices, which is often also formalised with agreements. They express long-term commitments for finding solutions based on forecasting the scale and persistence of the issue [83]. Cooperation and partnerships can be adopted for stakeholders at different stages of the supply chain to avoid landfill treatment and to procure a green pathway for waste management [32].
- RQ3: We could not find an explicit answer to the question about how a country such as Australia should manage future solar PV panel waste, including through existing policies. The practical relevance and impact on current environmental and economic challenges are yet to be fully and properly addressed in the available literature. Only a few studies bridge the gap between research and real-world applications, including policy development, industry best practices and technological innovations for recycling and waste management. The review shows there is need for more interdisciplinary studies that combine technological solutions with the economic, environmental and social dimensions of the problem.

In short, the literature on the solar photovoltaics value chain and EOL management practices has plenty of descriptive data but lacks critical analysis on scientific validity, research evaluation and practical relevance. Future research should address these gaps by adding more methodological rigour, integrated lifecycle thinking and the real-world applicability of research outcomes. This is key to developing effective strategies for the sustainability and economic viability of the solar photovoltaics industry. If such solutions are not found, we risk replacing the climate change challenges with problems related to plastics, toxic pollution and waste volumes.

7. Future Research

The review of the published literature shows that analysis of the photovoltaic industry is often done in a scattered manner, and predominantly from a technological standpoint. There is definite evidence that more effort, research and analysis of economic and social sectors are required to understand the comprehensive and dynamic relationship between the different consumer and producer sectors to participate in a circular economy for solar systems. Many aspects of CBMs have not been explored, despite the fast uptake of solar PV technology. Based on the gaps identified through the SLR, the following list of questions are suggested for future study:

1. What will be the effects of the lack of raw materials for making solar panels or the effect of toxic substances released during the recovery of failed panels? Is the risk of recycling panels superior to the risk of causing negative health impacts?
2. What is the estimated recovery rate and cost of reusing or recycling waste?
3. If the recovery of solar panels creates jobs, would the increase in jobs created be significant?
4. Given the lack of raw materials and the inability of some countries to produce or recover solar cells, when could solar PV technology be considered as a main method of energy production in the majority of countries?
5. What are the circular policies, economic programs and circular technologies of advanced countries for solar PV systems?

Given the complexity of a circular PV industry, answering some of these questions with the aid of quantitative complex system methods such as system dynamics or agent-based modelling might be appropriate. According to the studies reviewed, the social, economic and environmental sectors of society will be impacted by analysis related to circular modelling, determining the appropriate scenario for the development of the solar cell industry, and the implementation of long-term and short-term plans.

8. Conclusions

Solar cell facilities are rapidly increasing because of attention being given by industry, policy makers and energy planners to reduce climate change through decarbonisation, to diminish the production of pollutants, diversify the energy sector and ensure energy security. The growing use of solar cell technology globally will inevitably increase wastage associated with solar panels. Accordingly, there is a need to adopt a suitable framework to move away from traditional ways for managing waste, and to develop new models. Circularity needs to penetrate the entire value chain of solar PV systems and apply to all current and to the potential new generation of photovoltaics, and systems thinking is necessary for implementing a circular framework for the entire solar PV value chain.

Rather than being treated as waste, such solar components should be considered as raw materials for the development of a new industry based on the recycling and reuse of discarded solar panels. This issue itself requires the implementation of a circular model. The currently existing CBMs include product–service systems, second-life models and EOL management, but they all need wider adoption to be able to deliver waste elimination. Circular strategies need to be implemented in all stages of the PV value chain to achieve sustainability. Supporting policies should be implemented for this, and trained professional and educational initiatives are necessary. All in all, considering the existing challenges, innovative value policies and programs should be created to resolve the obstacles as, if left to the market alone, this is unlikely to happen.

In conclusion, the analysis presented here underscores the significance of embracing circular economy principles—business models and recycling systems for EOL solar PV panels. Circular economy principles are instrumental in attaining economic, environmental and social sustainability goals, and such principles should not be overlooked. Based on fully refereed papers published in high-quality journals, the systematic literature review took a multidisciplinary approach, looking for solutions. The insights from the analysis show that there are multiple factors obstructing the adoption of circularity, including conflicting industry interests, weak legislation and lack of awareness about or willingness to address the significance of the problem. On the other hand, collaborations and partnerships along the entire value chain are essential in finding appropriate solutions. While these aspects are generally recognised, there are currently no wide-reaching real-world approaches that combine technological and sustainable solutions to a problem that is only likely to increase in scale.

This holistic systematic literature review of global research focussed on the importance of forward thinking in solar PV EOL management and is the first to look for solutions and identify gaps in current research. It revealed thematic trends in research interest but also highlighted the current lack of reliable and scalable circular economy solutions. Positioned at the cusp between theory and practice, it offers insights for policymakers, industry and researchers, highlighting the importance of future work that bridges the gap between theoretical concepts, industry practice, legislation and business models. It also emphasises the need for stakeholder inclusivity, variety in approaches and diversity in emerging technological solutions, and also acknowledges the importance of environmental and social impact assessments as part of the uptake of any innovation.

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