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CIRCULAR ECONOMY IN PHOTOVOLTAICS: AN ANALYSIS OF GLOBAL REGULATIONS AND THEIR IMPLICATIONS IN BRAZIL

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ABSTRACT
With the expansion of the market, the volume of waste generated by this sector is also growing. However, in several countries, regulations for the management of this waste at the end of its useful life are still inadequate, in part because the amount of solar modules discarded so far has been relatively low. This study reviews the value chain of photovoltaic solar energy, focusing on the analysis of regulations aimed at the management of photovoltaic waste at the end of its useful life, both nationally and internationally. To this end, a bibliometric review was carried out that analyzed 654 peer-reviewed articles published in English. The results offer an overview of the global regulations and standards applied to the treatment of photovoltaic waste, providing useful information for entrepreneurs and public policy makers in the evaluation of future photovoltaic technologies and in the creation of guidelines for the management of this waste.

Keywords: Photovoltaic solar energy, Circular economy, Photovoltaic waste.

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INTRODUCTION

The global PV industry has shown steady growth over the past ten years, with an average annual rate of 26.5% between 2012 and 2021. This increase resulted in an approximate production of 1 TWh, corresponding to 3.6% of the total generation of electricity in the world (Bezerra, 2022; Maka & Alabid, 2022). It is estimated that in 2030 the global capacity could reach 2,840 GW, while in 2050 it could reach 8,500 GW (IRENA, 2016). This scenario reflects the growing importance of photovoltaic solar energy in the global energy matrix.

In Brazil, there is a clear expansion of photovoltaic solar energy. Normative Resolution No. 482, published on April 17, 2012 by the National Electric Energy Agency (ANEEL), gave a relevant boost to the sector. By May 2023, the installed capacity of solar photovoltaic energy in the country reached 28.9 GW, representing 13.1% of the national energy matrix (ABSOLAR, 2023). This growth highlights the strategic importance of solar energy in the Brazilian context.

However, the increase in installed capacity is accompanied by a growing concern with the management of waste generated by these systems. With obsolescence and facility failures, it is estimated that between 2030 and 2050, 60 to 78 million tons of PV module waste will be disposed of in landfills around the world (Franco & Groesser, 2021). This volume of waste highlights the urgent need to develop effective solutions for the management of this material.

The European Union (EU), aware of the potential environmental impacts of photovoltaic waste, was a pioneer in implementing the Waste Electrical and Electronic Equipment (WEEE) Directive, establishing specific regulations for the treatment of this waste. The directive requires Member States to report on the projection of photovoltaic waste and implement additional regulations for solid waste (Kim & Park, 2018). These initiatives aim to guide the PV industry towards a circular life cycle.

In Brazil, the advance in solid waste management was consolidated with the institution of the National Solid Waste Plan (PLANARES), through Decree No. 11,043, of April 13, 2022. This plan establishes guidelines and goals for solid waste management over the next two decades. However, PLANARES does not yet include specific guidelines for the treatment of photovoltaic waste, which highlights a gap in the country's environmental policy.

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In view of this scenario, this study proposes to carry out a bibliometric review to analyze the current functioning of the photovoltaic value chain and the public policies adopted in leading countries in photovoltaic waste management. The objective is to provide subsidies for an informed transition of the Brazilian photovoltaic industry to a circular economy, aligning with international best practices.

THEORETICAL FRAMEWORK

Understanding the development, manufacture, sale, and lifelong management of PV systems requires a value chain analysis, as highlighted by Franco and Groesser (2021). The introduction of the concept of circular process by Abdala and Sampaio (2018) presents itself as a network of production relations within a system, exerting direct or indirect influence on the independent and simultaneous existence of all the elements that make up the various reproducible groups, independently of the reproduction systems.

In this way, the circular economy aims to enable a systematic and ideal use and reuse of industrialized products, covering both durable and non-durable goods. This approach encompasses from the initial design phase of the project to beyond its reuse, thus contemplating the entire life cycle of the product.

In the face of increasing environmental deterioration and the global energy crisis, the development of clean and renewable energy technologies is essential. In this context, photovoltaic energy presents itself as one of the most sustainable and promising alternatives for energy generation.

Solar PV has experienced a notable increase in its capacity, registering a significant addition of 191,450 MW (IRENA, 2022). China stands out as a world leader, with the largest installed capacity for solar energy generation (De Souza Ribeiro Filho et al., 2022), with a total of 392 GW. In 2021 alone, 150 GW were added, and an average annual additions of 210 GW are projected during the period 2022 to 2030 (IRENA, 2022).

In 2016, the Energy Research Company (EPE) projected that Brazil would have an installed capacity of 25 GW in solar energy by 2030. However, in a recent revision of these projections, EPE updated the estimate, predicting that the country will reach 45.27 GW in installed capacity by 2031 (EPE, 2022). These figures reflect not only the remarkable growth of the sector in Brazil, but also its increasingly relevant position in the global solar energy scenario.

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In the photovoltaic industry, solar modules and energy storage systems contain materials that can be harmful to the environment, making it essential to implement effective end-of-life management of these technologies. This strategy seeks not only to mitigate environmental impacts but also to prevent shortages of critical materials, ensuring that future resource demands are met sustainably (Dos Santos et al., 2022).

According to the principles established by the Organization for Economic Cooperation and Development (OECD), manufacturers are responsible for monitoring their products throughout their life cycle, assuming both environmental and economic obligations. Thus, it is essential that the PV sector adopts a circular economy approach, especially with the continuous expansion of installed PV capacity globally. This growth leads to a considerable increase in the number of decommissioned PV modules (Sica et al., 2018).

These approaches require transformations across the entire value chain, from production to implementing new ways of converting waste into resources. At the same time, they contribute to the Sustainable Development Goals (SDGs) by proposing measures for the sustainable use of natural resources and waste recycling, promoting innovation and generating desirable financial returns, as well as broader economic benefits (Gil-Lamata & Latorre-Martínez, 2022).

Leading countries in installed capacity of solar sources, such as Italy, Australia, and South Korea, do not have specific legislation for the management of the end of life of solar photovoltaic modules, being limited to general waste legislation (Majewski et al., 2023). On the other hand, the European Union (EU), recognizing the possible environmental impact of photovoltaic waste, has established guidelines for Member States.

In these guidelines, the responsibility for the disposal and recycling of photovoltaic modules is assigned to the manufacturers. In addition, Member States must estimate and report to the European Commission on the amount of photovoltaic waste (Kim, Park, 2018). The EU also mandates that manufacturers label equipment to inform users that products must be recycled at the end of their life cycle. According to Ritzen et al. (2016), all EU Member States have adapted the WEEE Directive to their national legislations, implementing country-specific regulations.

In Brazil, the management of photovoltaic waste still lacks specific regulation and follows the guidelines of the National Solid Waste Policy, which classifies it in the category of electrical and electronic waste. According to Konzen and Pereira (2020), the 2010

National Solid Waste Policy defines the practices of reuse, recycling, and composting as environmentally appropriate final destination for solid waste. In addition, the legislative document addresses fundamental concepts such as life cycle, reverse logistics, shared responsibility, sustainable development, and prevention and precautionary principles. The relevance of these concepts in the environmentally responsible management of waste in the country is highlighted. This approach aims to promote practices that minimize environmental impacts, fostering sustainability and responsibility in the management of photovoltaic waste in the Brazilian context.

The reuse of solar modules is being addressed in Australia, although in a still small market. It is believed that there will be an escalation and development of the circular economy for the solar energy sector. As highlighted by Majewski et al. (2023), it would be necessary to establish a certification for solar modules for the purpose of ensuring that they meet safety and performance requirements. This certification should make it possible to track solar modules and establish guidelines for end-of-life legislation.

In South Korea, photovoltaic waste is categorized as industrial waste. However, the generation of this waste is not being monitored by the government, and there are no estimates or timelines for solar modules to reach the end of their life cycle (Kim & Park, 2018). The discussion on the subject in the country is recent, having been established in 2016 that the entities responsible for the disposal of industrial waste must manage this waste properly, seeking to reduce its quantity by building facilities specialized in waste reduction. In 2017, the South Korean government opened a photovoltaic waste recycling facility in North Chungcheong Province.

As per Gautam et al. (2021), India does not have specific regulations for the disposal of photovoltaic waste, using the MNRE guidelines. These guidelines state that manufacturers must ensure that PV waste is disposed of as per the 'E-waste (Management and Handling) Rules'. However, the authors point out that India, in 2019, was able to handle only 22% of the total e-waste generated in the country.

Thus, the relevance of analyzing the impacts on the circular economy of photovoltaic waste becomes evident, considering that it is already being treated in several countries. However, in Brazil, the topic is still incipient, with no specific legislation and supervision to manage the circular chain of the photovoltaic industry.

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METHODOLOGICAL PROCEDURES

This study adopts a descriptive methodology, according to the classification of Vergara (2006), because it presents specific characteristics of a phenomenon, in this case, the scientific publications on the value chain of photovoltaic solar energy, focusing on the analysis of regulations aimed at the management of photovoltaic waste at the end of its useful life, both nationally and internationally. The research is characterized as qualitative, following the methodological categories proposed by Richardson and Social (2008), and this approach was chosen to support the collection of data necessary for the construction of a Bibliographic Portfolio.

To explore the research questions, a literature review was conducted, a scientific process that, according to Cook, Mulrow, and Haynes (1997), is replicable and transparent, establishing a solid foundation for the advancement of knowledge in a specific field and the development of theories. The technique used for the systematic review was the Knowledge Development Process - Constructivist (ProKnow-C), as proposed by Ensslin, Ensslin, Lacerda and Tasca (2010). This instrument guided the search and selection of articles, allowing the creation of a bibliographic portfolio with the most relevant studies on the subject, an approach widely used in academic research in several areas.

The methodology adopted in this study aims to ensure that the selection of articles is conducted in a rigorous and judicious manner, offering a comprehensive and in-depth view of the scientific publications most pertinent to the topic investigated.

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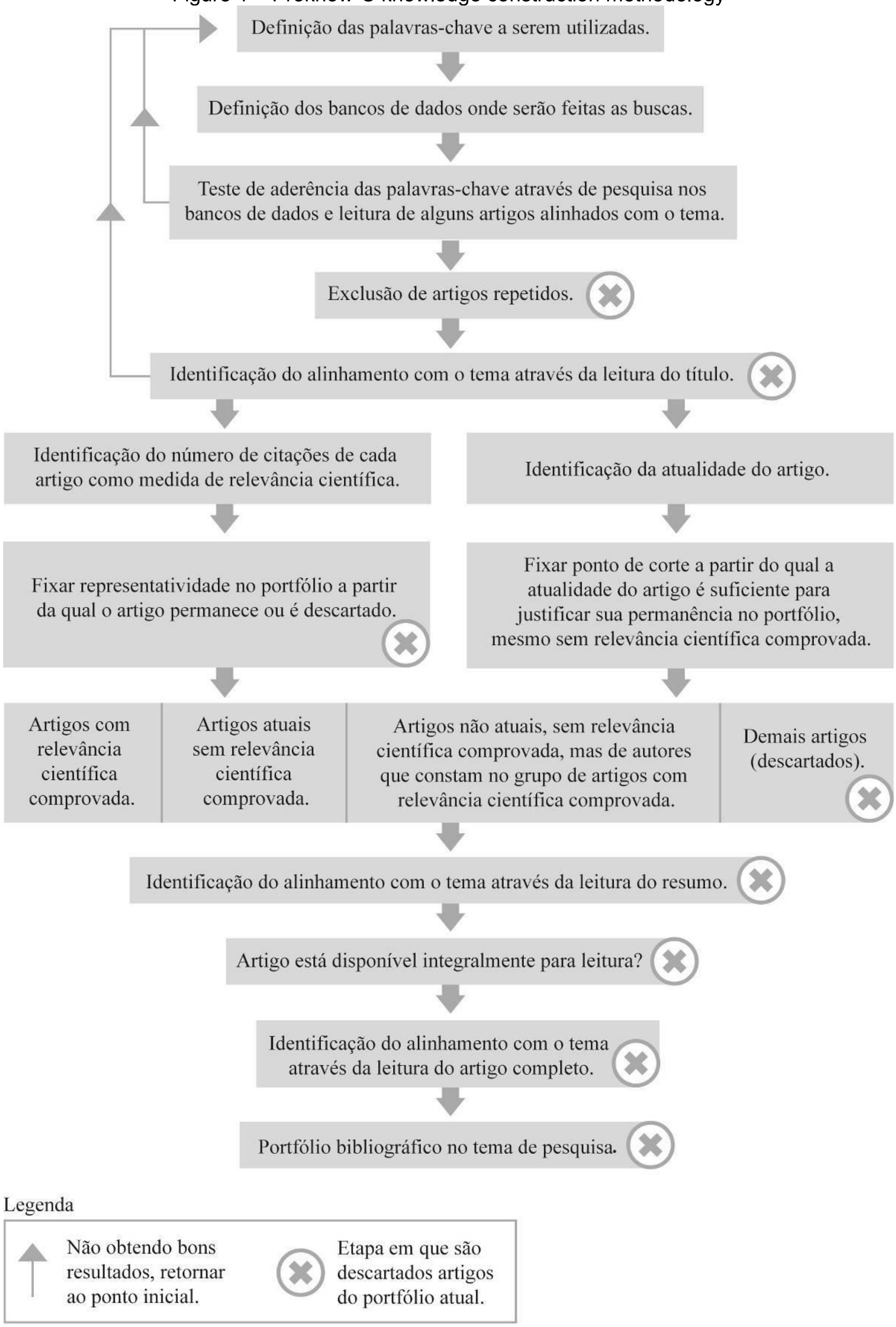
Figure 1 – Proknow-C knowledge construction methodology



Source: Ensslin; Ensslin; - Lacerda and Tasca (2010)

To format the Bibliographic Portfolio (PB), a cut-off point of 80% was established, thus calculating the representativeness of each article in the BP. Articles classified as scientifically recognized undergo an abstract analysis, and those aligned with the theme remain in the BP.

The literature search was conducted using the Web of Science database, ensuring the inclusion of high-quality peer-reviewed studies in our results (Denyer & Tranfield, 2009). We conducted a comprehensive search for peer-reviewed articles in English, with the purpose of including the most current knowledge available, especially in the context of the circular economy in the solar PV industry. This investigation was carried out in May 2023, covering the entire period available and including articles published up to that month.

Table 1 – Summary of the Database Search

Keywords	Database	Quantity
economy circular and solar energy	Web of Science	416
economy circular and photovoltaic energy		181
economy circular and solar modules		57

Source: Prepared by the authors with data extracted from the Web of Science

The VOSviewer software was used, recognized for its effectiveness in the creation and exploration of network-based bibliometric maps (Boyack et al., 2018). The choice of this software for bibliometric analysis was justified by several reasons: I) its intuitive graphical interface, which facilitated the visualization and interpretation of the data; II) its compatibility with the Web of Science database, allowing a more comprehensive analysis; and III) the fact that it is a freeware software, free of additional costs, which made it possible to use it in the research.

SEARCH RESULTS

As noted by Dos Santos et al. (2022), the growth of photovoltaic waste presents a new environmental challenge, requiring the development of industries focused on the recycling and reuse of solar modules. In the Brazilian scenario, it is essential to institute effective management, through policies that oblige producers of photovoltaic modules to assume both environmental and economic responsibilities.

To identify alternatives that contribute to the management of photovoltaic waste, a bibliometric review was carried out. In the search, using the set of keywords shown in Table 1, all the information obtained from the Web of Science database (title, abstract, authors, year of publication, place of publication, citations, country, keywords) were exported to

Microsoft Excel spreadsheets. The results were merged into one (n=654) and duplicates were identified (n=179). Once identified, they were removed from the consolidated bank.

In the next step, which involves the analysis of the titles of the articles in order to assess their relevance in relation to the research theme, a total of 346 articles were excluded, thus leaving 129 articles that proved to be congruent with the scope of the investigation. At this stage, the selection criteria covered the approach to the theme of the circular economy of photovoltaic waste, with emphasis on the consideration of social, environmental and economic impacts. The justifications for the exclusion of the 346 articles were as follows: I) The content was not aligned with the focus of this research; II) Access to the articles was restricted; III) The articles were considered overly technical, many of which focused on research related to extending the life of batteries and the application of solar modules for heating water.

Following the Proknow-C method, the 129 articles were ordered in descending citation mode, with 34 articles separated in repository A, defined by the ratio of 80% of the total citations over the total number of articles. Soon after, the remaining 95 articles were separated in repository B, of which 57 titles had 1 to 12 citations, and 22 had no citations.

After the analysis of the Authors' Database, 2 articles aligned with the theme were selected, which were added to repository A.

Table 2 – Bibliographic Portfolio of the research topic

#	Title	Quotes	Authors	Year Publication
1	Circular economy strategies for mitigating critical material supply issues	141	Gaustad, G; Krystofik, M; Bustamante, M; Badami, K	2018
2	Research and development priorities for silicon photovoltaic module recycling to support a circular economy	98	Heath, GA; Silverman, TJ; Kempe, M; Deceglie, M; Ravikumar, D; Remo, T; Cui, H; Sinha, P; Libby, C; Shaw, S; Komoto, K; Wambach, K; Butler, E; Barnes, T; Wade, A	2020
3	Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review	97	Salim, HK; Stewart, RA; Sahin, O; Dudley, M	2019
4	Management of end-of-life photovoltaic panels as a step towards a circular economy	83	Sica, D; Malandrino, O; Supino, S; Head, M; Padlocks, MC	2018

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5	Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules	72	Farrell, CC; Osman, AI; Doherty, R; Saad, M; Zhang, X; Murphy, A; Harrison, J; Vennard, ASM; Kumaravel, V; Al-Muhtaseb, AH; Rooney, DW	2020
6	Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification	46	Tsanakas, JA; van der Heide, A; Radavicius, T; Denafas, J; Lemaire, E; Wang, K; Poortmans, J; Voroshazi, E	2020
7	Assessment of the energy recovery potential of waste Photovoltaic modules	44	Farrell, C; Osman, AI; Zhang, XL; Murphy, A; Doherty, R; Morgan, K; Rooney, DW; Harrison, J; Coulter, R; Shen, D	2019
8	Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia	42	Mahmoudi, S; Huda, N; Behnia, M	2019
9	Adapting Stand-Alone Renewable Energy Technologies for the Circular Economy through Eco-Design and Recycling	38	Gallagher, J; Basu, B; Browne, M; Kenna, A; McCormack, S; Pilla, F; Styles, D	2019
10	Sustainable energy storage for solar home systems in rural Sub-Saharan Africa - A comparative examination of lifecycle aspects of battery technologies for circular economy, with emphasis on the South African context	37	Charles, RG; Davies, ML; Douglas, P; Hallin, IL; Mabbett, I	2019
11	Life cycle assessment for a solar energy system based on reuse components for developing countries	30	Kim, B; Azzaro-Pantel, C; Pietrzak-David, M; Maussion, P	2019
12	Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis	29	Mathur, N; Singh, S; Sutherland, JW	2020
13	The Role of Renewable Energy in the Promotion of Circular Urban Metabolism	27	Barragan-Escandon, A; Terrados-Cepeda, J; Zalamea-Leon, E	2017
14	PV Waste Management at the Crossroads of Circular Economy and Energy Transition: The Case of South Korea	24	Kim, H; Park, H	2018
15	Policies and Measures for Sustainable Management of Solar Panel End-of-Life in Italy	24	Malandrino, O; Sica, D; Head, M; Supine, S	2017

16	Life cycle assessment of a vanadium flow battery A joint organization of University of Aveiro (UA), School of Engineering of the Polytechnic of Porto (ISEP) and SCIence and Engineering Institute (SCIEI)	22	Gouveia, J; Mendes, A; Monteiro, R; Mata, TM; Caetano, NS; Martins, AA	2020
17	Sustainable industrial technology for recovery of Al nanocrystals, Si micro particles and Ag from solar cell wafer production waste	21	Yousef, S; Tatariants, M; Denafas, J; Makarevicius, V; Lukosiute, SI; Kruopiene, J	2019
18	Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios	20	Lisperguer, RC; Ceron, EM; Higueras, JD; Martin, RD	2020
19	A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels	20	Ansanelli, G; Fiorentino, G; Tammaro, M; Zucaro, A	2021
20	Design for Recycling Principles Applicable to Selected Clean Energy Technologies: Crystalline-Silicon Photovoltaic Modules, Electric Vehicle Batteries, and Wind Turbine Blades	19	Norgren, A; Carpenter, A; Heath, G	2020
21	The resources, exergetic and environmental footprint of the silicon photovoltaic circular economy: Assessment and opportunities	18	Bartie, NJ; Cobos-Becerra, YL; Frohling, M; Schlatmann, R; Reuter, MA	2021
22	Powering a Sustainable and Circular Economy-An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries	17	Desing, H; Widmer, R; Beloin-Saint-Pierre, D; Hischier, R; Wager, P	2019
23	Towards a circular economy: Investigating the critical success factors for a blockchain-based solar photovoltaic energy ecosystem in Turkey	16	Erol, I; Peker, I; On, IM; Turan, I; Searcy, C	2021
24	Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels	16	Alberti, J; Raigosa, J; Raugei, M; Assiego, R; Ribas-Tur, J; Garrido-Soriano, M; Zhang, LH; Song, GB; Hernandez, P; Fullana-i-Palmer, P	2019
25	Simulation-Based Exergy Analysis of Large Circular Economy Systems: Zinc Production Coupled to CdTe Photovoltaic Module Life Cycle	16	Llamas, AA; Bartie, NJ; Heibeck, M; Stelter, M; Reuter, MA	2020
26	Sustainable technology for mass production of Ag nanoparticles and Al microparticles from damaged solar cell wafers	15	Yousef, S; Tatariants, M; Tichonovas, M; Makarevicius, V	2019
27	A Systematic Literature Review of the Solar Photovoltaic Value Chain for a Circular Economy	14	Franco, MA; Groesser, SN	2021

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28	Review of State of the Art Recycling Methods in the Context of Dye Sensitized Solar Cells	14	Schoden, F; Dotter, M; Knefelkamp, D; Blachowicz, T; Hellkamp, ES	2021
29	Remanufacturing end-of-life silicon photovoltaics: Feasibility and viability analysis	14	Deng, R; Chang, N; Lunardi, MM; Dias, P; Bilbao, J; Ji, JJ; Chong, CM	2021
30	Holistic review of hybrid renewable energy in circular economy for valorization and management	13	Bist, N; Sircar, A; Yadav, K	2020
31	Life cycle assessment of a renewable energy generation system with a vanadium redox flow battery in a NZEB household A joint organization of University of Aveiro (UA), School of Engineering of the Polytechnic of Porto (ISEP) and SCIence and Engineering Institute (SCIEI)	13	Gouveia, JR; Silva, E; Mata, TM; Mendes, A; Caetano, NS; Martins, AA	2020
32	End-of-life CIGS photovoltaic panel: A source of secondary indium and gallium	13	Amato, A; Beolchini, F	2019
33	A set of principles for applying Circular Economy to the PV industry: Modeling a closed-loop material cycle system for crystalline photovoltaic panels	12	Contreras-Lisperguer, R; Muñoz-Cerón, E; Aguilera, J; de la Casa, J	2021
34	Upcycling Silicon Photovoltaic Waste into Thermoelectrics	12	Cao, J; Sim, Y; Tan, XY; Zheng, J; Chien, SW; Jia, N; Chen, KW; Tay, YB; Dong, JF; Yang, L; Ng, HK; Liu, HF; Tan, CKI; Xie, GF; Zhu, Q; Li, ZB; Zhang, G; Hu, L; Zheng, Y; Xu, JW; Yan, QY; Loh, XJ; Mathews, N; Wu, J; Suwardi, A	2022
35	Recycling and Reuse potential of NICE PV-Modules	5	Einhaus, Raw; Madon, F; Degaulange, J; Wambach, K; Denafus, J; Lorenzo, FR; Abalde, SC; Garcia, TD; Bowler, a	2018
36	Third Generation Photovoltaics - Early Intervention for Circular Economy and a Sustainable Future	2	Charles, RG; Davies, ML; Douglas, P	2016

Source: Prepared by the authors with data extracted from the Web of Science

The bibliometric portfolio indicates a growing interest in the academic community for research on the circular economy in the solar photovoltaic industry, with the publication of 36 articles between 2016 and 2022. As shown in Table 3, the main route of dissemination of

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the results was through academic journals. The journals with the highest number of publications were Resources Conservation and Recycling and Sustainability (n = 4), followed by Progress in Photovoltaics (n = 3) and Energies, Energy Reports, Journal of Cleaner Production, Journal of Sustainable Energy Reviews, Renewable & Sustainable Energy Reviews, and Sustainable Production and Consumption (n = 2). The ten most active journals accounted for 67% of the articles analyzed.

Finally, the results show that the circular economy theme of the solar PV industry is suitable for publication in a variety of peer-reviewed journals (n = 22) that focus primarily on sustainability, environment, and energy issues.

Table 3 – Number of publications per journal

Source	Articles
Resources Conservation and Recycling	4
Sustainability	4
Progress in Photovoltaics	3
Energies	2
Energy Reports	2
Journal of Cleaner Production	2
Journal of Sustainable Metallurgy	2
Renewable & Sustainable Energy Reviews	2
Sustainable Production and Consumption	2
2016 Electronics Goes Green 2016+	1
2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (wcpec)	1
Advanced Materials	1
Applied Energy	1
Energy	1
Energy for Sustainable Development	1
Environmental Technology & Innovation	1
Journal of Industrial Ecology	1
Nature Energy	1
Scientific Reports	1
Solar Energy Materials and Solar Cells	1
Sustainable Cities and Society	1
Waste Management	1

Source: Prepared by the authors with data extracted from the *Web of Science*

European countries and the United States of America have been at the forefront of academic publication regarding photovoltaic systems. Among all the articles reviewed, 56% had first authors working at a European institution, Germany, Spain, Lithuania and Italy. Asia has 21% of co-authors, driven by China's interest and investments in clean energy, mainly power generation through photovoltaic systems. This was followed by the Americas with 16% of co-authors.

According to Franco and Groesser (2021), developing countries have disadvantages compared to the European and Chinese situations. Although policies for the implementation

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of photovoltaic systems are being adopted in these countries, there is a lack of government investments for academic research.

Table 4 – Temporal distribution of geographic location by authorship

Country	Co-authorship	Country	Co-authorship	Country	Co-authorship
Germany	5	Wales	3	Brazil	1
Spain	5	Canada	2	Colombia	1
Italy	4	Chile	2	Ecuador	1
Lithuania	4	England	2	India	1
USA	4	Ireland	2	Oman	1
Australia	3	Japan	2	Poland	1
Egypt	3	Northern Ireland	2	Scotland	1
France	3	Portugal	2	Singapore	1
China	3	South Africa	2	South Korea	1
Switzerland	3	Belgium	1	Turkey	1

Source: Prepared by the authors with data extracted from the Web of Science

Table 5 highlights the authors with the largest number of published articles in the selected bibliographic portfolio, it is highlighted that the first ten authors have academic recognition and are cited in several studies. Regarding the recognition of authors, a total of 192 different authors were observed in the articles in the portfolio.

Table 5 – Main authors of the portfolio

Authors	Documents	Quotes
Denafas, Julius	3	72
Bartie, N.J.	2	37
Caetano, N. S.	2	35
Charles, Rhys G.	2	39
Davies, Matthew I.	2	39
Douglas, Peter	2	39
Makarevicius, Lives	2	36
Malandrino, Ornella	2	108
Martins, A. A.	2	35
Mata, T. M.	2	35

Source: Prepared by the authors with data extracted from the Web of Science

It is important to note that there are no researchers or research groups with predominant prominence (Figure 2). The analysis of the relationship network between authors and co-authors reveals the existence of small research groups that publish together.

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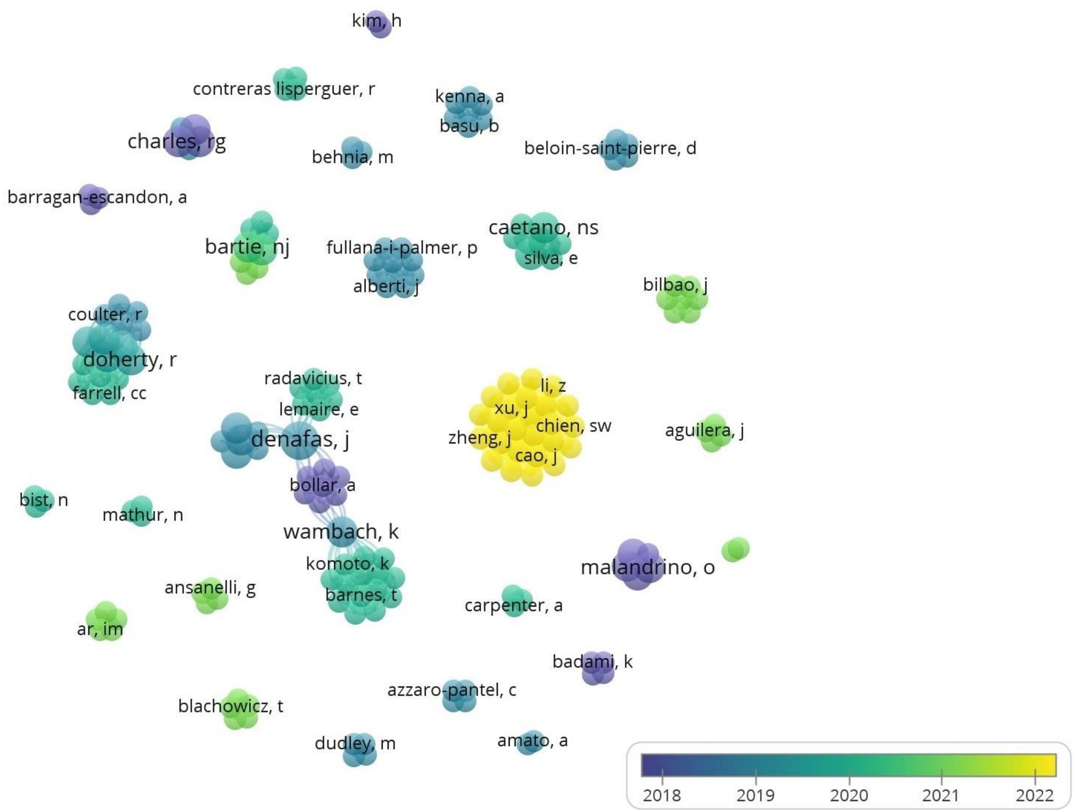
Figure 2 – Relationship of authors in the portfolio



Source: Prepared by the authors with data extracted from the Web of Science

Table 6 shows the ten most cited works by the authors within the selected portfolio.

Table 6 – Most cited works in the portfolio

Title	Approach	Authors	Citations received by the selected portfolio
Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels	The paper presents transparent and detailed assessments and information related to the End-of-Life Cycle Assessment (LCA) of silicon PV modules, offering thorough environmental analysis on the procedures developed for the recycling of crystalline PV modules. For this analysis, ISO 14040 standards were applied to FRELP - Full Recovery End of Life Photovoltaic. Researchers have played a key role in spreading the innovative process of recycling waste PV modules, contributing significantly to its wider adoption. The results obtained also played an important role in guiding policy decisions related to the topic, providing valuable information for the formulation of more effective public policies in photovoltaic waste management.	LATUNUSSA et al. (2016)	12
Management of end-of-life photovoltaic panels as a step	The objective of the research was to analyze the contribution of the photovoltaic sector to energy demands and to promote a closed-loop economy, based on sharing, leasing, reuse, repair, rehabilitation	SICA et al. (2018)	10

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towards a circular economy	and recycling, valuing energy and natural resources and minimizing the production of photovoltaic waste. The research theme was addressed by the European Commission, where it included measures and actions to develop a circular economy in all value chains, involving all actors in the processes (production and consumption). This change required changes between the 'upstream' and 'downstream' segments, requiring the implementation of innovative waste management and reverse logistics paths.		
Review on feasible recycling pathways and technologies of solar photovoltaic modules	The research addresses the increase in photovoltaic waste, debating the possible environmental damage caused by toxic substances that can be released from photovoltaic modules and the risk of scarcity of natural resources for semiconductor materials. The authors address the issue of photovoltaic module recycling through three distinct approaches: the recycling of manufacturing waste, the recycling of discarded modules, and the practice of remanufacturing and reusing the modules themselves. The results of the research show that technologies aimed at recycling modules at the end of their useful life are being widely explored, and there are even some options available in the market. However, significant challenges remain regarding process efficiency, simplification of procedure complexity, energy demand, and the use of chemical substances.	TAO; YU (2015)	10
Global status of recycling waste solar panels: A review	The article brings a review and discussion of the status of the life cycle assessment of photovoltaic waste, addressing types of modules used; production of modules and the generation of waste; recycling techniques; recycling policies adopted by EU Member States, following the WEEE Directive and from countries outside the EU market. The authors propose that a recycling standard be developed for the photovoltaic industry, requiring manufacturers to be responsible for recycling and that governments adopt policies and regulations to encourage the recycling and safe disposal of photovoltaic waste.	XU et al. (2018)	10
A techno-economic review of silicon photovoltaic module recycling	The authors reviewed cutting-edge recycling technology and associated it with a quantitative economic assessment to better understand the economic barrier presented. The techno-economic review made it possible to identify the essential framework and technological changes needed to overcome the current barrier to implementing commercial-scale recycling. The cost structure for recycling five different types of modules was demonstrated, each using three distinct methods of recycling. All of them are more expensive than landfill, which is a disincentive to recycling. Government regulation is critical to enabling recycling and breaking the economic barrier.	DENG et al. (2019)	9
Strategy and technology to recycle wafer-silicon solar modules	In this work, the authors propose a recycling process for wafer-Si modules, presenting two new technologies (electroextraction and sheet resistance monitoring), reducing the amount of photovoltaic waste in landfills.	HUANG et al. (2017)	8
Experimental investigations for	The paper reports on a new procedure for the resource recovery of residual PV modules, where it obtained the	KANG et al. (2012)	8

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recycling of silicon and glass from waste photovoltaic modules	recovered silicon yield at 86%. The authors found a pure silicon yield with a purity of 99.999% and tempered glass recovered from the residual photovoltaic module. As a result, it was possible to optimize the recovery process of silicon metal by means of a surface treatment on the photovoltaic modules.		
Producer responsibility and recycling solar photovoltaic modules	The article explores the need for policies aimed at the recycling of photovoltaic waste, evaluating the existing recycling protocols for the five main types of PV materials marketed (indium, gallium, silicon, cadmium sulfide, cadmium and tellurium). It was found that for most PV devices, the economic motivation for recycling does not outweigh the difference between recycling and landfill disposal costs, making recycling an economically unviable alternative without adequate incentives. Despite this, some companies in the solar energy sector have voluntarily started recycling solar modules, possibly driven by environmental responsibility, rather than economic advantages.	MCDONALD; PEARCE (2010)	8
Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling	The authors compared the innovative recycling process 'FRELP' with the other processes used in European WEEE recycling plants, noting that the innovative process meets the recycling targets set by European legislation. Finally, they question that the low amount of photovoltaic waste collected is discouraging investments in industrial processes for recycling and address that such a situation is not a justification for delaying research in this field.	ARDENT; LATUNUSSA; BLENGINI (2019)	7
Crystalline Silicon Photovoltaic Recycling Planning: Macro and Micro Perspectives	The authors developed mathematical models to evaluate the profitability of recycling technologies and to assist in strategic decisions about the optimal location of photovoltaic waste treatment centers, essential for the disposal of products at the end of their useful life. The study also presents reverse logistics alternatives, proposing solutions for the transport of photovoltaic waste from various collection facilities to treatment centers.	CHOI; FTHENAKIS (2014)	7

Source: Prepared by the authors with data extracted from the Web of Science.

The articles reported which factors may contribute to the circular economy, seeking the valorization of waste with a focus on the recovery of photovoltaic waste and the consequent environmental, economic and social benefits. The demonstration of new processes to enable the recycling of photovoltaic waste was the biggest discussion in the co-cited articles, demonstrating the academic interest in contributing with new technologies and making such action economically viable.

For the textual analysis of the keywords extracted in the articles of the portfolio, the software VOSviewer and Microsoft Excel were used, where a total of 262 occurrences were allowed, all of which were distinct. Graph 1 and Figure 3 show the bibliometric analysis of the keywords with frequency above 1 and their connections. The most frequent are "circular economy" and "recycling".

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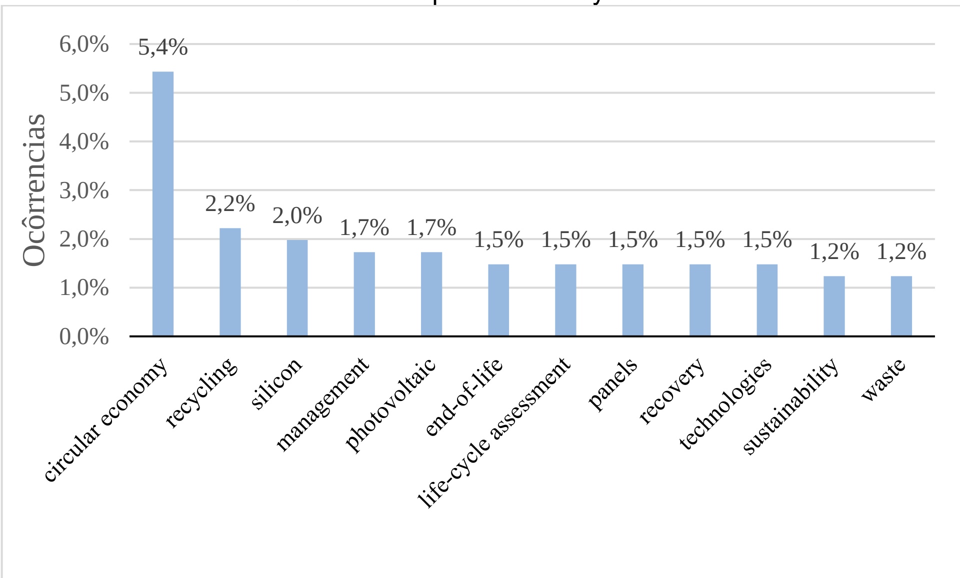
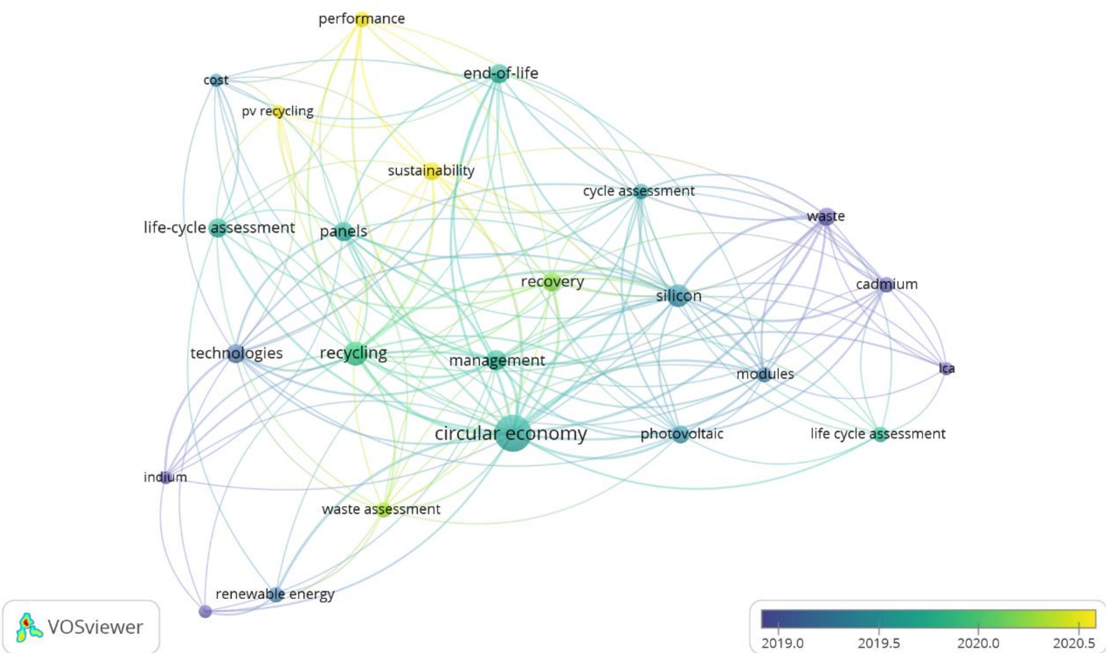
Chart 1 – Top Portfolio Keywords



Source: Prepared by the authors with data extracted from the Web of Science

Figure 3 – Main Keywords in the Portfolio



Source: Prepared by the authors with data extracted from the Web of Science

The words "circular economy" and "recycling" are generic and are used in other areas of research, being relevant and applicable to the circular economy theme of the photovoltaic systems industry.

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DISCUSSION

The transition to a circular economy in the photovoltaic sector requires a restructuring of value chains and the adoption of new sustainable business models. While solar PV is a promising source of clean energy, the increase in waste generated by damaged or obsolete solar modules presents a growing challenge, underlining the importance of public policies and technological innovations to ensure the sustainability of the sector.

The European Union (EU) has excelled in the implementation of regulations aimed at the management of this waste, as demonstrated by the Waste Electrical and Electronic Equipment (WEEE) Directive. Implemented in Germany in 2015, this directive makes manufacturers responsible for the disposal and recycling of solar modules, using the Business-to-Business (B2B) model (Kim & Park, 2018). The mandatory estimation and reporting on photovoltaic waste generation and material recovery in Germany emphasizes the importance of this management model (PV Cycle, 2016; Majewski et al., 2023).

However, the economic viability of photovoltaic waste recycling is still an obstacle, especially given the high costs involved. Different approaches, such as the Japanese system, where consumers pay a fee at the end of their useful life, and the Swedish model, where the State takes over the collection of waste, show how these challenges are faced in different contexts (Sasaki, 2004). Implementing recycling fees can provide the necessary financial resources to support these practices, as suggested by Monier et al. (2014), although there are debates about the appropriateness of such fees in clean energy systems (Dias et al., 2018).

In Brazil, photovoltaic waste management is guided by the National Solid Waste Policy, which treats modules as part of electronic waste, without specific guidelines for the photovoltaic industry (Konzen & Pereira, 2020). The lack of specific regulation prevents the development of a robust circular economy in the sector, which reinforces the need to adapt and implement regulatory models based on successful international experiences (Majewski et al., 2021).

The low recycling rate of Waste Electrical and Electronic Equipment (WEEE) in Brazil, where only 3% of the 2 million tons produced in 2019 was recycled, highlights the urgency of a collaborative approach between the business community, government agencies, and civil society (Forti et al., 2020; Gagliardi et al., 2023). Promoting sustainability as a business priority is important to drive the transformation towards the circular economy.

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Therefore, the circular economy in the photovoltaic sector requires an approach that includes technological innovation, the implementation of appropriate public policies, and the creation of sustainable business models. The combination of these strategies can mitigate environmental impacts and generate economic and social benefits. Collaboration between all those involved is essential for the expansion of solar energy to occur in a sustainable way.

FINAL CONSIDERATIONS

The transition to a circular economy in the photovoltaic industry in Brazil is an important step, especially as solar energy gains more space and challenges arise in waste management. Implementing specific policies and regulations that cover the entire value chain, from production to disposal, is important to ensure that the growth of this industry is sustainable. The European Union's experience with the WEEE Directive can serve as a model adaptable to the Brazilian context to help mitigate environmental impacts.

Improper disposal of photovoltaic waste in landfills or the environment can compromise the benefits associated with solar energy. This reinforces the need to take measures to ensure proper management of these materials. The absence of specific regulations in Brazil to deal with this waste highlights the urgency of actions that include efficient inspection, ensuring compliance with standards and preventing environmental damage.

The literature highlights the importance of continuous investments in research and development to improve recycling and reuse technologies for photovoltaic components. In view of this, the present study carried out a bibliometric review using the Proknow-C method, which identified 129 relevant publications among 654 articles analyzed, evidencing the growing academic interest in the area. These studies reinforce the need for technological advances to optimize waste management, allowing for more efficient recycling and the creation of new economic opportunities.

In addition, the awareness and engagement of the different groups involved, such as manufacturers, consumers, and government agencies, is also essential for the success of a circular economy in the photovoltaic sector. Education about sustainable practices and the importance of the circular economy can promote the cultural change necessary to integrate these practices into everyday life. Collaboration among all those involved is key to creating an environment conducive to sustainability.

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To ensure that the growth of photovoltaic energy in Brazil is sustainable, it is necessary to advance in the creation of specific regulations, invest in technological innovation, and promote social awareness. These measures not only mitigate the environmental impacts of photovoltaic waste but also position the country for a more effective transition to a circular economy in the energy sector.

REFERENCES

1. Abdalla, F. A., & Sampaio, A. C. F. (2018). Os novos princípios e conceitos inovadores da economia circular. Entorno Geográfico, (15), 82-102.

2. ABSOLAR. (2021). Brasil 4º país que mais cresceu em 2021. Recuperado de https://www.absolar.org.br/noticia/energia-solarfotovoltaica-brasil-e-4o-pais-que-mais-cresceu-em-2021/. Acesso em: 30 mai. 2023.

3. ABSOLAR. (2022). Panorama da solar fotovoltaica no Brasil e no mundo. Recuperado de https://www.absolar.org.br/mercado/infografico/. Acesso em: 21 abr. 2022.

4. Agenda 2030. (2022). ODS – Objetivos de Desenvolvimento Sustentável. Recuperado de https://brasil.un.org/pt-br/sdgs. Acesso em: 05 set. 2022.

5. Bezerra, F. D. (2022). Agropecuária: micro e minigeração distribuída e suas perspectivas com a Lei 14.300/2022. Fortaleza: BNB. Caderno Setorial Etene, 7(234), ago. 2022.

6. Boyack, K. W., van Eck, N. J., Colavizza, G., & Waltman, L. (2018). Characterizing in-text citations in scientific articles: A large-scale analysis. Journal of Informetrics, 12(1), 59-73.

7. Brasil. (2010). Lei n.º 12.305, de 02 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei nº 9.605, de 12 de fevereiro de 1998; e dá outras providências. Recuperado de https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm. Acesso em: 05 set. 2022.

8. Brasil. Ministério do Meio Ambiente. Secretaria de Qualidade Ambiental. (2022). Plano Nacional de Resíduos Sólidos - Planares [recurso eletrônico]. Coordenação de André Luiz Felisberto França... [et al.]. Brasília, DF: MMA. Recuperado de https://sinir.gov.br/informacoes/plano-nacional-de-residuos-solidos/. Acesso em: 05 set. 2022.

9. Cook, D. J., Mulrow, C. D., & Haynes, R. B. (1997). Systematic reviews: Synthesis of best evidence for clinical decisions. Annals of Internal Medicine, 126(5), 376-380.

10. De Souza Ribeiro Filho, L. A., Pereira, V. L., & Velázquez, S. M. S. G. (2022). Simulador de Energia Solar para Implementação de Sistemas Fotovoltaicos no Contexto Urbano. Revista Mackenzie de Engenharia e Computação, 22(1), 82-104.

11. Denyer, D., & Tranfield, D. (2009). Producing a systematic review.

12. Dias, P., Bernardes, A. M., & Huda, N. (2018). Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. Journal of Cleaner Production, 197, 750-764.

13. Dos Santos, M. R., de Brito, J. L. R., & Shibao, F. Y. (2022). Economia circular e a energia solar fotovoltaica. Colóquio - Revista do Desenvolvimento Regional, 19(1), 293-311.

14. Empresa de Pesquisa Energética (Brasil). (2021). Balanço Energético Nacional 2021: Ano base 2020. Rio de Janeiro: EPE.

15. Ensslin, L., Ensslin, S. R., Lacerda, R. T. D. O., & Tasca, J. E. (2010). ProKnow-C, Knowledge Development Process – Constructivist: Processo técnico com patente de registro pendente junto ao INPI. Brasil: [sn].

16. Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The global e-waste monitor 2020. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam, 120.

17. Franco, M. A., & Groesser, S. N. (2021). A systematic literature review of the solar photovoltaic value chain for a circular economy. Sustainability, 13(17), 9615.

18. Gagliardi, S. F., Ferreira, J. B., Solon, A. S., & Frascati, G. (2023). Logística reversa: uma análise dos indicadores de sustentabilidade das organizações de recicladores de Uberlândia-MG. Revista ADMPG, 13.

19. Gautam, A., Shankar, R., & Vrat, P. (2021). End-of-life solar photovoltaic e-waste assessment in India: A step towards a circular economy. Sustainable Production and Consumption, 26, 65-77.

20. Gil-Lamata, M., & Latorre-Martínez, M. P. (2022). The circular economy and sustainability: A systematic literature review. Cuadernos de Gestión (Bilbao), (ART-2022-128134).

21. IRENA. (2016). End-of-life management: Solar photovoltaic panels. International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems.

22. IRENA. (2022). IRENA's energy transition support to strengthen climate action: Insight to impact. International Renewable Energy Agency.

23. Kim, H., & Park, H. (2018). PV waste management at the crossroads of circular economy and energy transition: The case of South Korea. Sustainability, 10(10), 3565.

24. Konzen, B. A. D. V., & Pereira, A. F. (2020). Gestão de resíduo fotovoltaico: Revisão bibliográfica sobre o cenário de fim de vida do sistema. In Congresso Brasileiro de Energia Solar - CBENS.

25. Majewski, P., Al-shammari, W., Dudley, M., Jit, J., Lee, S. H., Myoung-Kug, K., & Sung-Jim, K. (2021). Recycling of solar PV panels: Product stewardship and regulatory approaches. Energy Policy, 149, 112062.

26. Majewski, P., Deng, R., Dias, P. R., & Jones, M. (2023). Product stewardship considerations for solar photovoltaic panels. AIMS Energy, 11(1), 140-155.

27. Maka, A. O. M., & Alabid, J. M. (2022). Solar energy technology and its roles in sustainable development. Clean Energy, 6(3), 476-483.

Revista ARACÊ
ISSN: 2358-2472

28. Monier, V., et al. (2014). Development of Guidance on Extended Producer Responsibility (EPR).

29. Richardson, R. J. (2008). Métodos e técnicas (3ª ed.). São Paulo: Atlas.

30. Ritzen, M., et al. (2016). IEA-PVPS Task 15. In Proceedings of the 48th IEA PVPS Executive Committee Meeting, Vienna, Austria (pp. 15-16).

31. Sasaki, K. (2004). Examining the waste from electrical and electronic equipment management systems in Japan and Sweden. Lund University Master's Programme in Environmental Science, Lund, Sweden. 30pp.

32. Sica, D., Malandrino, O., Supino, S., Testa, M., & Lucchetti, M. C. (2018). Management of end-of-life photovoltaic panels as a step towards a circular economy. Renewable and Sustainable Energy Reviews, 82, 2934-2945.

33. Vergara, S. C. (2006). Projetos e relatórios de pesquisa. São Paulo: Atlas.