FORECAST OF WASTE GENERATION FROM PHOTOVOLTAIC MODULES IN BRAZIL: A PROSPECTIVE ANALYSIS

Raimundo G. Saraiva Jr[1], Elizeu L. M. Barboza[1], Kaline K. L. Oliveira[1] and Francisco G. C. Almeida[1]

1 Federal Institute of Education, Science, and Technology of the State of Ceará, Limoeiro do Norte (Brazil)

Abstract

The growth of solar energy in Brazil is beneficial for both the environment and the country's energy supply. However, it poses challenges related to managing the end-of-life of solar panels. This study aims to estimate the amount of solid waste resulting from the future end-of-life of these panels in Brazil, focusing on the period 2042 to 2049, using data from the National Electric Energy Agency and technical parameters obtained from reports by international agencies. This is a quantitative, descriptive study based on technical parameters, including power per panel, predominant technology, estimated useful life, and historical solar energy generation. The results indicate that panels installed between 2017 and 2024 could generate up to 2.1 million tons of waste, including approximately 631 tons of lead. There is an urgent need to develop public policies that effectively manage photovoltaic waste, thereby mitigating environmental and public health impacts. This work contributes to the understanding of the problem, stimulates debate on sustainability in the solar energy sector, and proposes a replicable prospective model for national estimates of photovoltaic waste.

Keywords: Photovoltaic Energy, Solid Waste, Solar Panels, Sustainability, Environmental Policy, Lead.

1. Introduction

In recent decades, the expansion of solar photovoltaic energy in Brazil has intensified, driven by the guidelines of the 2030 Agenda and Sustainable Development Goal 12, which promote sustainable production and consumption patterns (United Nations, 2025). This growth is considered a fundamental strategy for diversifying and decarbonizing the national energy matrix. However, the widespread adoption of this technology poses significant environmental challenges, particularly regarding waste management at the end of the photovoltaic modules' life cycle, as they can contain hazardous substances such as lead and cadmium.

Regarding the end-of-life phase of photovoltaic panels, Hestin and Monier (2011) emphasize that improper disposal of this equipment can lead to significant environmental impacts and risks to human health. Among the main problems, the authors mention the potential leaching of toxic elements, such as lead and cadmium, which can contaminate soil and water resources. Furthermore, improper disposal results in the loss of valuable and widely used materials, such as glass and aluminum, as well as rare metals like silver, indium, gallium, and germanium, thereby compromising resource recovery and the sustainability of the production cycle. Several other studies have also addressed this issue (Costa et al., 2024; Romel and Ng, 2024; Sharma et al., 2024).

The typical solar panel life cycle is shown in Table 1. On average, a photovoltaic module has a useful life of 25 to 30 years (IEA, 2022) and is used for power generation. Considering the growth of solar installations over the last two decades, Brazil is expected to experience exponential growth in the volume of end-of-life panels from the 2040s onward, underscoring the need for advanced planning for their disposal.

Table 1: Typical solar panel life cycle

25 to 30 years of use (IEA, 2022)	End of life cycle
Operating in power generation	Reuse (Daljit Singh, 2021)
	Recycling (Das and Sarmah, 2025)
	Disposal

Source: prepared by the author.

Table 1 lists possible destinations for end-of-life panels, highlighting the options for reuse, recycling, and

10.18086/swc.2025.09.05 Available at http://proceedings.ises.org

disposal. Treating waste from end-of-life photovoltaic modules is necessary, given their large volumes and the potential presence of polluting or financially valuable constituent elements. As a suggestion, waste management approaches could follow a hierarchy that prioritizes the reuse or recycling of components, seeking to avoid disposal.

Reuse is environmentally preferable because it conserves the resources and energy embodied in the original product. Panels over 25 years old still retain approximately 80% of their electricity generation capacity (Özkalay et al., 2025) and can be reallocated to lower-energy applications, such as street lighting, rural systems, and microgeneration in isolated communities. This practice can reduce CO_2 emissions associated with the module life cycle by up to 40% if the useful life is doubled (Daljit Singh, 2021). Reuse can also be achieved with panels reconditioned using a two-step Ag/Cu electrodeposition process, with the aim of repairing and reusing degraded c-Si solar cells (Mo et al., 2020).

Panel recycling is an essential alternative when reuse is not feasible. The process involves the disassembly, separation, and purification of materials such as glass, aluminum, silicon, silver, and copper, which account for over 90% of the module's total mass. The photovoltaic panel recycling process involves three main steps: disassembly, delamination, and material purification.

Disassembly involves removing the aluminum frame and the junction box with copper wires, a relatively simple step that can be performed manually or automated, allowing these components to be sent to consolidated recycling chains (Das and Sarmah, 2025).

Delamination, considered the greatest challenge, aims to separate the glass and silicon cells from the encapsulant. Among the methods used, heat treatment heats the panel to 500–650°C, decomposing the polymers and releasing glass and silicon. Although it is energy-intensive and can generate toxic emissions, such as hydrogen fluoride, it also damages cells, with a recovery rate of 70–80% (Ndalloka et al., 2024; Rubino et al., 2021). Chemical treatment dissolves the encapsulant using solvents, allowing for the recovery of silicon and glass with greater integrity, reaching 90–95% efficiency; however, it generates hazardous liquid waste and is slower (Chowdhury et al., 2020; Das and Sarmah, 2025). Mechanical treatment crushes the panels and physically separates the materials, being faster and of high capacity, but with lower efficiency (60–70%) and lower value of the recovered materials (Piedrahita et al., 2025). Advanced techniques, such as the "hot knife", use heated blades to separate glass and encapsulant in about 50 seconds per module (Das and Sarmah, 2025; Ndalloka et al., 2024).

The final stage is the purification of the metals, usually through hydrometallurgical processes. Chemical leaching, often with nitric acid, dissolves metals such as silver, copper, and lead (Ndalloka et al., 2024). Selective processes, such as Gold-REC1, allow the recovery of over 99% of the silver in 120 minutes, leaving silicon as a high-purity residue (Romano et al., 2024). The metals are then recovered by electrodeposition or chemical precipitation, achieving an efficiency of over 95% (Das and Sarmah, 2025).

In terms of efficiency, the combined use of different steps increases recycling efficiency. The advanced process PhotoLife achieved 82% recycling and 94% overall recovery, including energy recovery of the encapsulant (Rubino et al., 2021), while PV CYCLE reported 96% recovery for crystalline silicon panels (Bajagain et al., 2020). However, economic viability remains limited, as the costs of logistics, energy, and labor often exceed the value of the recovered materials. Silver accounts for approximately 46% of the recoverable value, estimated at US$72 per 100 kg of panels. The economy only becomes viable on a large scale, with a return on investment of about 3.35 years (Rubino et al., 2021). Regarding the environmental impact, recycling significantly reduces CO_2 emissions, potentially avoiding between 1,480 and 2,220 tons of CO_2 by recycling 185 tons of panels (Piedrahita et al., 2025).

Recent technologies have achieved recycling efficiencies ranging from 80% to 95%, particularly in automated shredding, electrostatic separation, and chemical purification systems (Das and Sarmah, 2025). International experiences, such as those of Henan Recycle (Henan Recycle Equipment Co., 2025), demonstrate that it is possible to recover materials with a purity greater than 95%, highlighting the potential for industrial applications of these technologies.

Currently, most discarded solar panels end up in landfills. It is estimated that only 10% of solar panels are recycled globally at the end of their life cycle. Europe stands out from the rest of the world, managing to recycle up to 80% of solar panel waste (Bajagain et al., 2020; Piedrahita et al., 2025). In Brazil, the recycling rate is low and undetermined, possibly falling below 10%. Despite global progress in photovoltaic waste management, Brazil lacks detailed national estimates and specific regulations governing this area.

The main risk associated with landfill disposal is the leaching of toxic and hazardous materials present in the panels (Bajagain et al., 2020; Das and Sarmah, 2025). Components such as lead and cadmium can leach out of damaged or degraded panels over time, contaminating soil and groundwater (Das and Sarmah, 2025). This contamination poses a direct threat to ecosystems and human health (Bajagain et al., 2020). Although some studies suggest that landfill disposal may be safe under ideal conditions, in practice, panels can break during transportation or disposal, increasing the risk of releasing these toxic components (Daljit Singh et al., 2021; Chowdhury et al., 2020). In addition to environmental risks, landfill disposal represents a significant loss of valuable resources that could be reintegrated into the economy (Das and Sarmah, 2025). Solar panels are composed of materials such as aluminum, high-quality glass, silver, copper, and pure silicon (Daljit Singh et al., 2021). By discarding them, the opportunity to recover these materials through recycling is lost, which would increase the need for extracting new raw materials, a process with its own environmental and economic costs.

The treatment of waste from end-of-life solar panels is considered a significant challenge to the sustainability of solar energy, as although the technology is clean during operation, inadequate management of its waste can lead to negative environmental consequences (Chowdhury et al., 2020).

The Brazilian scenario still presents structural challenges for the consolidation of a circular economy in the photovoltaic sector. The lack of specific technical standards, certification for refurbished modules, and industrial-scale recycling infrastructure limits the advancement of sustainable waste management. Furthermore, the lack of economic incentives and organized reverse logistics prevents recoverable materials from being efficiently reinserted into production chains.

Although Brazil established the National Solid Waste Policy (PNRS) with Law No. 12,305 of August 2, 2010, a regulatory gap remains regarding specific standards and the effective implementation of reverse logistics for solar panels. Several bills specifically addressing the treatment of solar panel waste are pending in the National Congress. Bill No. 3784 of 2023, proposed in the Federal Senate, addresses the creation of a mandatory reverse logistics system for photovoltaic solar panels, amending the PNRS. In the Federal Chamber, Bill No. 998 of 2024 establishes the Policy to Incentivize the Development of Reverse Logistics for Photovoltaic Panels.

Considering this scenario, this study aims to estimate the generation of solid waste resulting from the end of the life cycle of photovoltaic modules in Brazil, with a specific focus on the period from 2042 to 2049. The research seeks to support the development of environmentally friendly waste management strategies, aligned with the principles of sustainability and the circular economy, thus strengthening public policies for a sustainable energy transition.

This article is organized as follows: the next section presents the methods, techniques, and procedures used to conduct the research, ensuring its organization, rigor, and objectivity. Section 3 discusses the results, and Section 4 presents the conclusions and recommendations.

2. Methodology

This work uses official solar power deployment data published by the National Electric Energy Agency (ANEEL), which regulates and monitors the production, transmission, distribution, and commercialization of electricity in Brazil. ANEEL's database (ANEEL, 2025) is updated daily and provides detailed information on distributed generation in all 27 states since 2009, including photovoltaic, wind, and other sources. The data acquired for this research on September 22, 2025, totaled 1.4 Gigabytes and was processed using Python.

This is a quantitative, descriptive study based on technical parameters, including the average power generated by the panel, the predominant technology, estimated useful life, and historical solar energy generation during the specified period. The methodology presented here has limitations in that it does not consider variable degradation, repowering, early replacement, technological and operational variations, and other variables. Therefore, it is not a viable estimate of the volume of waste generated by solar panels at the end of their life cycle.

The processing of data obtained from ANEEL enabled us to compile the annual installed photovoltaic power of photovoltaic projects in Brazil for the study period covered by this work, from 2017 to 2024. The results are presented in Table 2, with the values expressed in watts (W).

Table 2: Amount of photovoltaic power installed in Brazil each year.

Year	Output power (W)	Year	Output power (W)
2017	125,496,010	2021	4,682,715,690
2018	417,685,850	2022	8,172,734,840
2019	1,579,376,830	2023	8,580,284,780
2020	2,944,351,470	2024	10,083,735,470

Source: prepared by the author based on ANEEL (2025).

The constant evolution of solar panel construction has resulted in improved power generation performance each year. The International Energy Agency's (IEA, 2022) special report on global solar photovoltaic supply chains and the Fraunhofer Institute for Solar Energy Systems' (Philipps et al., 2025) report on photovoltaics indicate that the average power generation of Mono-PERC photovoltaic panels from 2017 to 2024 can be summarized as shown in Table 3. Panels with Mono-PERC technology, a type of passivated monocrystalline silicon, are the most widely used globally and are largely predominant in Brazil.

Table 3: Average power generated by the photovoltaic panel.

Year	2017	2018	2019	2020	2021	2022	2023	2024
Output power (W)	365	380	405	450	455	460	580	650

Source: prepared by the author based on IEA (2022) and Philipps et al. (2025).

The useful life of a solar panel depends on its quality, local climate conditions, usage, and regular maintenance. It is generally estimated to be between 25 and 30 years (IEA, 2022; Jordan and Kurtz, 2012). This study will use a 25-year useful life, during which it is projected that the solar panel will lose approximately 20% of its energy generation efficiency (Özkalay et al., 2025). Using the data from Table 2 (P_i= annual installed photovoltaic power) and Table 3 (P_{mp} = average solar panel power), we can estimate the number of solar panels installed in Brazil between 2017 and 2024, which will reach the end of their life cycle between 2042 and 2049. Considering that the average weight of a crystalline silicon photovoltaic panel (W_m = average solar panel weight) is 30 kilograms (IEA, 2022), we can estimate the total weight of solar panels (W_t) that will reach the end of their life cycle between 2042 and 2049, using Equation 1.

$$W_t = \frac{P_i}{P_{mp}} \times W_m \qquad \text{(eq. 1)}$$

Table 4 consolidates the results of the calculation of the annual volume of solar panels expected to reach the end of their life cycle between 2042 and 2049 in Brazil. The values are expressed in tons.

Table 4: Estimated total volume of solar panels that will reach the end of their life cycle between 2042 and 2049 in Brazil.

Year	2042	2043	2044	2045	2046	2047	2048	2049
Weight (W_t) (tons)	10,314	32,975	116,990	196,290	308,750	533,004	443,807	465,403

Source: prepared by the author.

Solar panels are manufactured using an industrial process that uses various elements in their composition. This study utilized the chemical composition of crystalline silicon solar panels as published in the IEA's special report on global solar photovoltaic supply chains (IEA, 2022).

Table 5 shows the percentage range of each chemical element in the solar panel composition (column [A]) and the average percentage of each chemical element used in this study (column [B]). The composition refers to crystalline silicon photovoltaic panels.

Table 5: Material composition of crystalline silicon photovoltaic panels.

Composition chemical	Percentage [A]	Percentage adopted [B]
Glass	68-72%	70%
Aluminum	12-14%	13%
Polymers	8-10%	9%
Silicon	3-4%	3.5%
Copper	2-4%	3%
Silver	0.03-0.08%	0.055%
Zinc	0.03-0.1%	0.065%
Lead	0.01-0.05%	0.03%
Tin	0.01-0.05%	0.03%
Others	0.20%	1.32%

(Column A) Source: IEA (2022).
(Column B) Source: prepared by the author based on IEA (2022).

.

In the following session, results produced by this methodology will be presented, considering the annual production of solar energy throughout the Brazilian territory, in each of the five Brazilian geographic regions, and in each federal unit.

3. Results and Discussion

3.1. National waste estimate and material composition

Based on data on the estimated total volume of solar panels that will reach the end of their life cycle between 2042 and 2049 in Brazil (Table 4) and the material composition of photovoltaic modules (Table 5 – column B), it was possible to estimate the amount of waste resulting from the end of the life cycle of solar panels in Brazil, year by year, with a breakdown of each material used in the solar panel production process. Table 6 presents the annualized results for each solar panel component.

Table 6: Material composition of crystalline silicon photovoltaic modules.

Material	2042	2043	2044	2045	2046	2047	2048	2049
Glass	7,220	23,083	81,893	137,403	216,125	373,103	310,665	325,782
Aluminum	1,341	4,287	15,209	25,518	40,138	69,291	57,695	60,502
Polymers	928	2,968	10,529	17,666	27,788	47,970	39,943	41,886
Silicon	361	1,154	4,095	6,870	10,806	18,655	15,533	16,289
Copper	309	989	3,510	5,889	9,263	15,990	13,314	13,962
Silver	**6**	**18**	**64**	**108**	**170**	**293**	**244**	**256**
Zinc	7	21	76	128	201	346	288	303
Lead	**3**	**10**	**35**	**59**	**93**	**160**	**133**	**140**
Tin	3	10	35	59	93	160	133	140
Others	136	435	1,544	2,591	4,076	7,036	5,858	6,143
Total	*10,314*	*32,975*	*116,990*	*196,290*	*308,750*	*533,004*	*443,807*	*465,403*

Source: prepared by the author.

Analyzing the results presented in Table 6, it can be stated that Brazil is expected to produce approximately 2,107,533 tons of waste resulting from the end-of-life cycle of solar panels between 2042 and 2049.

3.2. Critical metals

Among the components present in this waste, silver and lead are the most notable. Silver could reach a volume of 1,159 tons in this eight-year period, potentially representing an opportunity to explore the economic potential of this material. Lead could reach a volume of 632 tons in the eight years, becoming a concern for human health and the environment if this waste is not properly treated. Figure 1 highlights the evolution of lead and silver volumes from 2042 to 2049, measured in tons.

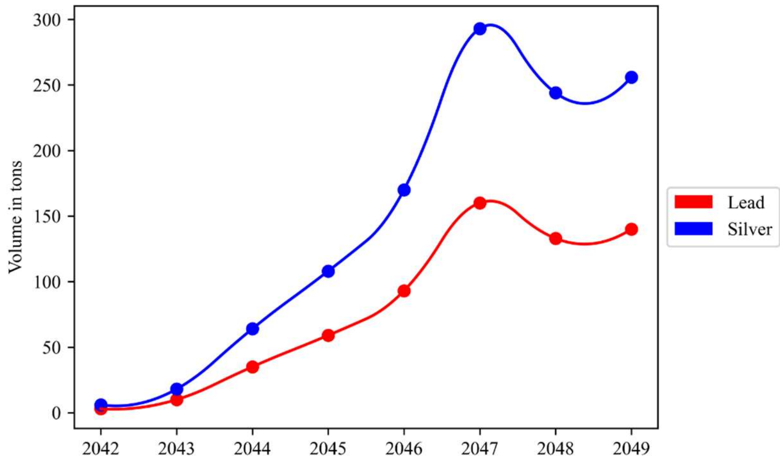

Figure 1: Estimated annual volume of lead and silver from end-of-life solar panels in Brazil, measured in tons between 2042 and 2049. Source: prepared by the author.

3.3. Regional distribution and logistical implications

Also based on data provided by ANEEL and using the methodology presented here, it was possible to estimate the volume of solar panels that will reach the end of their life cycle between 2042 and 2049 in each of the five Brazilian regions: South, Northeast, North, Southeast, and Central West. The results are consolidated in Table 7.

Table 7: Estimated volume of solar panels at the end of their life cycle between 2042 and 2049 in Brazil, by region.

Region	2042	2043	2044	2045	2046	2047	2048	2049
South	2,957	10,148	35,883	46,258	75,941	139,995	89,193	72,308
Northeast	1,498	5,271	16,643	35,635	62,202	105,012	96,316	111,227
North	303	1,043	4,561	11,151	21,368	33,751	35,243	42,366
Southeast	4,436	11,936	41,433	70,236	102,854	179,060	150,685	150,000
Midwest	1,120	4,577	18,471	33,010	46,901	75,186	72,371	89,502

Source: prepared by the author.

A graph of Table 7 is shown in Figure 2, where a break in the growth trend in panel volume is evident at the end of their life cycle in 2048. This likely reflects what occurred 25 years ago, in 2023, when the Brazilian integrated electricity system began to experience power reductions or outages (curtailment) due to excessive solar and wind generation, which was putting the stability of the Brazilian electricity system at risk. Curtailment became a new operational policy established by the ONS (National System Operator) following the August 15, 2023, blackout, which affected approximately 29 million people in 25 Brazilian states and the Federal District.

In 2024, only the southern region of Brazil failed to surpass the volumes of solar panels from 2023, largely due to the region being hit by a climate catastrophe that year, characterized by high rainfall levels and major socioeconomic and environmental impacts.

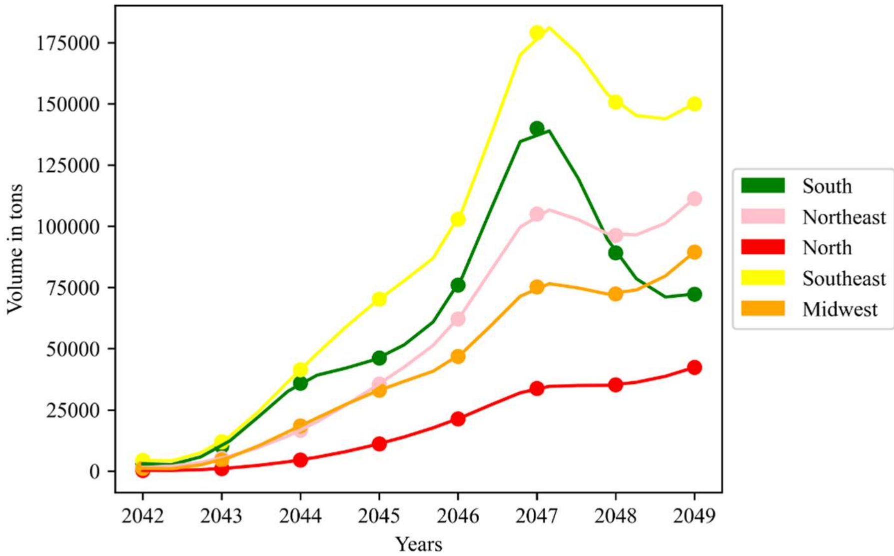

Figure 2: Estimated volume of solar panels at the end of their life cycle between 2042 and 2049 in Brazil, by region. Source: prepared by the author.

Of the 27 Brazilian states (26 states and 1 Federal District), some states stand out for having the largest volumes of solar panels per region during the study period. Figure 3 highlights (in black) the geographic position of these states within each of the five regions on a map of Brazil. In the South, Paraná is the state with the largest volume of panels. In the Northeast, it is Bahia. In the North, it is Amazonas. In the Southeast, it is São Paulo, and in the Central-West region, it is Mato Grosso. Of all these states, São Paulo had the largest number of solar panels during the study period.

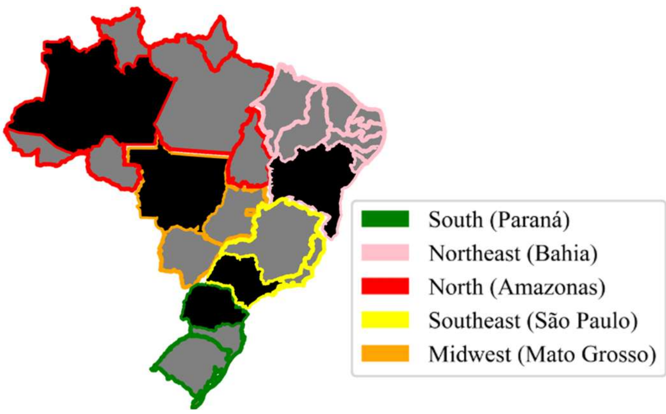

Figure 3: Identification (in black) of the state with the highest solar power, in each of the 5 regions in Brazil. Source: own elaboration.

Identifying the states with the largest number of solar panels by region may suggest that the Brazilian national waste policy, arising from solar panels, has a regional focus, facilitating logistics and prioritizing the cost-benefit ratio, thereby enabling the reduction of waste that would otherwise be discarded without proper treatment.

3.4. Perspectives on reuse and recycling

Technological alternatives for reusing and recycling solar waste are available to the Brazilian state, and it is urgent to update the legislation that establishes guidelines for the adequate management and integrated management of solid waste in the country, in the search to protect health and the environment, reduce the volume of waste, promote reuse, recycling, and treatment, and encourage reverse logistics.

4. Conclusion

The decommissioning of solar panels in Brazil could generate more than 2.1 million tons of waste by 2049, including 631 tons of lead, which raises serious environmental and public health concerns if this material ends up in landfills or is otherwise disposed of in the natural environment. Economic opportunities also emerge when it is estimated that 1,159 tons of silver could be generated from end-of-life solar panel waste, sparking interest in the Brazilian industrial complex in recycling these materials.

Reuse and recycling present themselves as viable alternatives for treating this waste, and Europe demonstrates their effectiveness, with up to 80% of solar panel waste being recycled. Brazil's socioeconomic differences also create opportunities for reuse, where panels can be reallocated to applications with lower energy demands, such as public lighting, rural systems, and microgeneration in isolated or economically vulnerable communities. The development of regional pilot recycling plants could be an alternative to strengthen the national solar waste treatment policy.

Although there is still time, updating legislation is urgent, along with revising public policies, offering fiscal incentives for reverse logistics, establishing regulatory frameworks and waste management strategies to ensure safe recycling, defining responsibilities throughout the production chain, and promoting a sustainable energy transition.

5. References

National Electric Energy Agency (ANEEL)., 2025. SIGA — ANEEL Generation Information System [dataset]. ANEEL Open Data. Available at: https://dadosabertos.aneel.gov.br/dataset/siga-sistema-de-informacoes-de-geracao-da-aneel/resource/11ec447d-698d-4ab8-977f-b424d5deee6a (Accessed: 22 September 2025).

Bajagain, R., Panthi, G., An, Y.-J. and Jeong, S.-W., 2020. Current practices on solar photovoltaic waste management: An overview of the potential risk and regulatory approaches of the photovoltaic waste. Journal of Korean Society of Environmental Engineers, 42(12), 690–708. Available at: https://doi.org/10.4491/KSEE.2020.42.12.690.

Chowdhury, MS, Rahman, KS, Chowdhury, T., Nuthammachot, N., Techato , K., Akhtaruzzaman, M., Tiong, SK, Sopian , K. and Amin, N., 2020. An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews, 27, 100431. Available at: https://doi.org/10.1016/j.esr.2019.100431.

Costa, HRS, Camargo, PLT, Alves, F. da S., 2024. Environmental impacts caused by the life cycle of photovoltaic panels. ForScience, 11(1), p. e01210. Available at: https://doi.org/10.29069/forscience.2023v11n1.e1210.

Daljit Singh, J.K., Molinari, G., Bui, J., Soltani, B., Rajarathnam, GP and Abbas, A., 2021. Life Cycle Assessment of Disposed and Recycled End-of-Life Photovoltaic Panels in Australia. Sustainability, 13(19), 11025. Available at: https://doi.org/10.3390/su131911025.

Das, H.J. and Sarmah, N., 2025. Photovoltaic module recycling: A review on material recovery methods and waste management approach. Solar Energy, 299, 113708. Available at: https://doi.org/10.1016/j.solener.2025.113708.

Henan Recycle Equipment Co., Ltd. MachineryRecycle – Lithium battery and solar panel recycling machine solutions. Available at: https://www.machineryrecycle.com (Accessed: 20 October 2025).

Hestin, M. and Monier, V., 2011. Study on Photovoltaic Panels – Supplementing the Impact Assessment for a Recast of the WEEE Directive. Paris: Bio Intelligence Service for the European Commission, DG Environment. Available at: https://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PV%20Panels%20-%20Final%20Report.pdf

International Energy Agency (IEA). 2022. Special report on solar PV global supply chains. Revised version, August 2022. Paris: International Energy Agency. Available at: https://www.iea.org/reports/special-report-on-solar-pv-global-supply-chains (Accessed: 3 October 2025).

Jordan, DC and Kurtz, SR 2012. Photovoltaic degradation rates — An analytical review. Progress in Photovoltaics: Research and Applications, Preprint NREL/JA-5200-51664, National Renewable Energy

Laboratory (NREL), Golden, CO, United States Department of Energy. Available at: https://www.osti.gov/bridge (Accessed: 10 October 2025).

Mo, L., Zhao, L., Zhou, C., Wang, G., Jia, X. and Wang, W., 2020. Ag/Cu plating to improve Ag grid electrodes of the recycled c-Si solar cells. International Journal of Electrochemical Science, 15, 11920–11928. Available at: https://doi.org/10.20964/2020.12.77.

Ndalloka, ZN, Nair, HV, Alpert, S. and Schmid, C., 2024. Solar photovoltaic recycling strategies. Solar Energy, 270, 112379. Available at: https://doi.org/10.1016/j.solener.2024.112379.

Özkalay , E., Quest, H., Gassner, A., Virtuani , A., Eder, GC, Vorstoffel , S., Buerhop -Lutz, C., Friesen, G., Ballif, C., Burri, M. and Bucher, C., 2025. Three decades, three climates: environmental and material impacts on the long-term reliability of photovoltaic modules. EES Solar, 1, 580–599. Available at: https://doi.org/10.1039/d4el00040d

Philipps, S., Warmuth, W. and Burger, B. 2025. Photovoltaics Report. Freiburg: Fraunhofer Institute for Solar Energy Systems ISE, with support from PSE Projects GmbH. Updated 29 May 2025. Available at: https://www.ise.fraunhofer.de (Accessed: 20 October 2025)

Piedrahita, A., Cárdenas, L.M. and Zapata, S., 2025. Solar Panel Waste Management: Challenges, Opportunities, and the Path to a Circular Economy. Energies, 18(7), 1844. Available at: https://doi.org/10.3390/en18071844.

Romano, P., Lanzone, C., Rahmati, S., Ippolito, N.M., Ferella, F. and Vegliò, F. 2024. A Kinetic Study of Silver Extraction from End-of-Life Photovoltaic Panels through Gold-REC1 Process. Sustainability, 16(17), 7846. Available at: https://doi.org/10.3390/su16177846.

Romel, M., Kabir, G. and Ng, KTW, 2024. Prediction of photovoltaic waste generation in Canada using regression-based model. Environmental Science and Pollution Research International, 31(6), 8650–8665. https://doi.org/10.1007/s11356-023-31628-9.

Rubino, A., Schiavi, P.G., Altimari, P. and Pagnanelli, F., 2021. Valorization of polymeric fractions and metals from end-of-life photovoltaic panels. Waste Management, 122, 89–99. Available at: https://doi.org/10.1016/j.wasman.2020.12.037.

Sharma, A., Mahajan, P. and Garg, R., 2024. End-of-life solar photovoltaic panel waste management in India: forecasting and environmental impact assessment. *Int. J. Environ. Sci. Technol.* 21, 1961–1980. https://doi.org/10.1007/s13762-023-04953-2.

United Nations. Goal 12: Ensure sustainable consumption and production patterns. United Nations Department of Economic and Social Affairs – Sustainable Development. Available at: https://sdgs.un.org/goals/goal12 (Accessed: 20 October 2025).