RECYCLING OF SOLAR PANELS: CHALLENGES AND SOLUTIONS FOR A SUSTAINABLE FUTURE

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Abstract

The growing adoption of solar photovoltaic (PV) technology has positioned it as a cornerstone of the global energy transition. However, the end-of-life phase of PV modules presents significant environmental and logistical challenges that require urgent and coordinated responses. This study investigates the recycling of solar panels within the Brazilian context, where regulatory frameworks specific to PV waste are still under development. PV modules are composed of materials such as glass, aluminum, silicon, and rare metals, which hold high economic and strategic value for the recycling industry. The research methodology includes a bibliographic review, an analysis of the European WEEE Directive, and case studies of the FREL process and automated disassembly systems, with particular attention to their potential adaptation to Brazil's regulatory and infrastructural landscape. Furthermore, the study examines reverse logistics mechanisms and current waste management practices for PV systems in Brazil. The findings highlight the importance of implementing inclusive public policies, reinforcing accredited PV recycling centers, and adopting emerging technologies to promote environmental sustainability. Ultimately, the research demonstrates that effective recycling of PV modules is essential to ensure that the environmental impacts associated with waste do not offset the benefits of renewable energy deployment.

Keywords: Solar energy, Recycling, Sustainability, Waste management, Circular economy, Reverse logistics, Photovoltaic panels.

1. Introduction

Access to energy is a fundamental right that directly influences the social, economic, and environmental development of populations (Souza, 2018). However, millions of people around the world, especially in vulnerable communities, still face significant barriers to accessing energy sources adequately and sustainably (Oliveira and Silva, 2020). This situation not only compromises people's quality of life but also limits the social, economic, and environmental development of communities, perpetuating cycles of poverty and inequality. The transition to renewable energies represents not only a strategy to mitigate the impacts of climate change but also an opportunity to promote greater social inclusion and to address energy inequalities (Martins et al., 2021).

In vulnerable communities, access to renewable energy sources is often limited by economic, social, and geographic factors. These constraints reinforce a condition of energy exclusion, which directly affects quality of life and limits development opportunities for these groups (Almeida and Ribeiro, 2022). In this context, energy justice emerges as a central concept, advocating that access to energy must be fair and equitable, taking into account the specific needs of marginalized communities (Ferreira; Lima, 2019). According to recent studies, the implementation of inclusive policies and accessible technologies can enable a more equitable and sustainable energy transition, benefiting the most vulnerable populations (Gomes et al., 2020).

In this context, renewable energy sources emerge as a promising solution to address the challenges of energy exclusion. Technologies such as solar, wind, and biomass provide sustainable alternatives that can be implemented in decentralized ways, enabling isolated and low-income communities to access energy more

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cleanly and affordably (Irena, 2021). The potential of renewable energy goes beyond reducing dependence on fossil fuels, as it also promotes social inclusion and strengthens the autonomy of communities (Ren21, 2023).

Thus, the popularization of photovoltaic solar panels as a renewable energy source signals important progress toward a more sustainable future. However, as the installation of these systems grows, a new challenge arises: the disposal and recycling of solar panels at the end of their life cycle (Irena, 2016). Energy efficiency and resource sustainability must be complemented by effective waste management strategies, especially considering the environmental impacts that may result from the improper disposal of photovoltaic materials (Godoy, 2024).

Research on glass reuse, rather than disposal, reveals that the adoption of incentive policies can be essential to increase recycling rates and enable more sustainable waste management (Unep, 2018). Both policies to stimulate research and development and environmental education play a vital role in moving toward more sustainable waste management methods (Oecd, 2021).

Glass is one of the most advantageous materials from a recycling perspective, as it can be reused indefinitely without loss of quality (Feve, 2019). According to the *Solid Waste Panorama in Brazil 2024*, published by the Brazilian Association of Waste and Environment (Abrema), for each 1 kg of glass sent for recycling, 1 kg of new material is obtained, highlighting a highly efficient process consistent with the principles of the circular economy.

Considering that glass represents a significant portion of the total mass of photovoltaic modules, its proper recovery is strategic both from an environmental and an economic perspective. The reintegration of this material into the production cycle contributes to reducing landfill disposal, saving natural resources, and lowering the energy consumption required for the manufacture of new inputs (Belancon et al., 2021).

This investigation analyzes the stage of Brazilian policy regarding the development of a sustainable logistics system for solar panels, identifies the logistical guidelines adopted to expand the use of these devices, and examines new techniques applied, considering the reuse of photovoltaic components and the most recent findings in other countries.

According to the International Renewable Energy Agency (Irena, 2020), waste generation from photovoltaic modules could reach up to 78 million tons by 2050. This scenario poses significant management challenges but also creates opportunities for the recovery of critical materials such as silver, aluminum, and silicon, thereby contributing to the security of strategic resources. Studies further indicate that countries such as Germany, Japan, and the United States have already advanced in formulating specific public policies for the disposal and recycling of solar panels, while in Brazil, such regulations are still at an early stage (Iea, 2022).

2. **Methodology**

This research adopts a qualitative approach, based on a bibliographic and documentary review. Scientific articles, technical reports, and case studies focusing on the recycling of photovoltaic modules and the implementation of reverse logistics were analyzed, both in developed countries and in emerging contexts (Martins et al., 2024).

To ensure scientific rigor, a bibliographic review was conducted using databases such as ScienceDirect, Scopus, and ResearchGate. The search employed keywords including “photovoltaic recycling,” “reverse logistics solar panels,” and “circular economy PV.” Priority was given to articles published between 2013 and 2024, in both English and Portuguese, with a focus on studies addressing the end-of-life phase of photovoltaic modules, material recovery, and environmental impacts. As an exclusion criterion, publications lacking technical data or addressing only economic aspects without a direct link to recycling or reverse logistics were disregarded, in accordance with the guidelines proposed by Kitchenham (2004) for systematic literature reviews.

The comparative analysis was structured into three axes: technological (processes such as the European FRELP and Japanese solutions for automated disassembly), regulatory (experiences of the European Union and still incipient initiatives in Brazil), and environmental (indicators of glass, silicon, and precious metal recovery). To systematize the findings, the technique of content analysis was used (Bardin, 2011), which allowed the identification of convergences and gaps between international models and the Brazilian context. This methodological approach made it possible not only to gather information but also to propose adaptations of best practices to the national scenario, in line with the Brazilian National Solid Waste Policy – PNRS (Brazil, 2010).

The selection of sources prioritized publications in international databases, mainly due to the recognized quality and scientific relevance of their contents. The temporal scope of the research covered the last ten years, with searches primarily conducted in ScienceDirect and Scopus (Pranckute, 2021). Emphasis was placed on studies addressing end-of-life management of solar panels, material recovery, and the assessment of associated environmental impacts.

Among the international models investigated, the European Full Recovery End of Life Photovoltaic (FRELP) process stands out, which proposes a closed-loop recycling system for crystalline silicon modules (Doe and Riveiro Paulino, 2022). The technical and environmental data of this process were obtained from the study of Latunussa et al. (2016), allowing the understanding of the steps involved, material recovery rates, and the impacts associated with the treatment of photovoltaic waste.

Additionally, the adopted methodology incorporated a qualitative comparative analysis with regulatory experiences of the European Union, proposing adaptations to the Brazilian context in light of the guidelines established by the National Solid Waste Policy – PNRS (Law No. 12.305/2010). This analysis emphasized, above all, the principles of shared responsibility for the product life cycle and the need for the implementation of reverse logistics systems in the country (Brazil, 2010).

The PNRS establishes as one of its principles the recognition of solid waste as an economic asset and of social value, to be reused whenever possible. In this sense, the research sought to identify, in the analyzed documents, how different countries have been structuring systems for the collection, sorting, transportation, and proper final destination of photovoltaic modules, and how such experiences could be adapted to the Brazilian context, where there is still no specific regulation aimed at electronic waste from the solar sector (Iea-Pvps, 2020).

As a methodological strand, the analysis of strategies aligned with the concept of circular economy was adopted, considering alternatives to the linear model of production and consumption. To this end, studies and reports addressing the reintegration of materials into the production cycle through the recycling and remanufacturing of photovoltaic components, especially glass, aluminum, silicon, and precious metals, were examined (Weckend *et al,* 2016). The review allowed the mapping of initiatives based on sustainable design, component traceability, and recycling incentives with high added value.

Furthermore, this research adopts as a complementary methodological criterion the analysis of international experiences documented by multilateral agencies, such as the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS, 2020) and the International Renewable Energy Agency (Irena, 2021). This approach allows for systematic comparisons between different regulatory models, highlighting potential adaptations to the Brazilian context. To ensure greater reliability, technical reports from independent organizations, such as Fraunhofer ISE (2022), which detail efficiency indicators in photovoltaic recycling processes, were also considered.

According to Kirchherr et al. (2017), the circular economy seeks to maintain the value of products, materials, and resources in the economy for as long as possible, reducing waste generation to a minimum. The integration between the concepts of circular economy and reverse logistics was evaluated as essential for the formulation of guidelines that promote the sustainability of the solar production chain in Brazil, extending the useful life of resources and minimizing the environmental impacts associated with improper disposal.

3. **Theoretical Framework**

Within the state of the art, it is observed that in Brazil, electricity generation is predominantly hydraulic, accounting for approximately 44.6% of the current energy matrix, as illustrated in Figure 1 (Absolar, 2022).

Among the main benefits of solar energy is the reduction of approximately 70 million tons of carbon dioxide (CO_2) in the atmosphere (Silva et al., 2024). As it is a clean source and free from fossil fuels, the need to expand investments, government incentives, and research that make its production increasingly accessible and efficient is reinforced (Pedroso, 2023).

Considering that the service life of photovoltaic panels ranges from 20 to 30 years, their replacement at the end of this period generates a new environmental concern. The disposal of this post-use material results in solid waste, making it essential to develop strategies for its proper management in the future (Kusch and Mclellan, 2022).

According to a survey conducted by the Brazilian Photovoltaic Solar Energy Association (Absolar, 2022), from January to the beginning of October of this year, solar energy grew by 44.4%, increasing from 13.8 GW to 20 GW. In the last 120 days, the growth rate has been nearly 1 GW per month, placing the source in the third position of the Brazilian electric matrix (June: 15.8 GW, July: 16.4 GW, August: 17.5 GW, September: 18.6 GW, October: 20 GW).

At the international level, it is observed that countries such as China and India, the main producers of solar energy, face challenges similar to those of Brazil regarding the lack of consolidated infrastructure for the management of photovoltaic waste (Chowdhury et al., 2020). However, recent initiatives, such as the adoption of circular economy guidelines and incentives for the recycling of critical components, have been identified as fundamental strategies to reduce environmental impacts and increase the competitiveness of the sector (Xu et al., 2022).

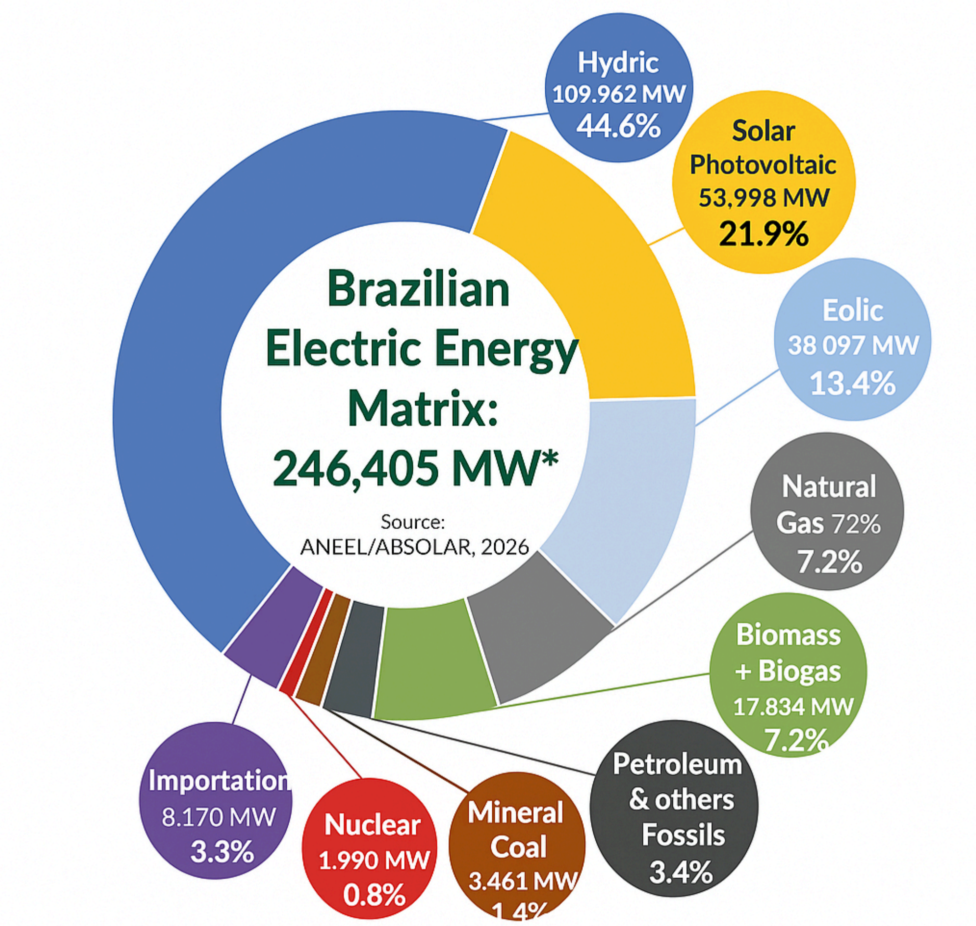

Fig. 1: Mapping of the Brazilian energy matrix and its respective percentages (ABSOLAR)

According to Anzileiro (2021), crystalline silicon (c-Si) solar panels are composed of a variety of materials, each with a specific function. Tempered glass provides both mechanical durability and optical clarity. The encapsulating material, known as Ethylene Vinyl Acetate (EVA), surrounds the photovoltaic cell, ensuring that the semiconductor element remains secure and preventing any undesired movement of the cells in case of impacts. In addition, the metallic copper contacts, coated with tin and lead and responsible for the electrical interconnection between the various cells of the panel, are presented in Table 1.

Tab. 1: Components of the PV module (Anzileiro, 2021)

Component	Porcentage (%)
Glass	70
Aluminum (frame)	18
Encapsulant (EVA)	5.1
Solar cell (c-Si)	3.65
Backsheet	1.5
Cable (copper an polymers)	1
Intemal conductor (Al)	0.53
Intemal conductor (Cu)	0.11
Sivel (Ag)	0.053
Other metals (Sn, Pb)	0.053
Total	100

According to Rystad Energy (2025), the main components of the panel with the highest value are aluminum, silver, copper, and polysilicon. Although silver accounts for approximately 0.05% of the total weight, it represents 14% of the total material value. Polysilicon, in turn, is produced through a process that requires a large amount of energy to reach the concentration necessary for solar panel efficiency, which is reflected in its relatively high resale price. The most widely used material is glass, which has a high recycling rate but is considered to have a low resale value.

The recycling process of a photovoltaic panel begins with its disassembly. At this stage, the aluminum frame and the junction box are removed from the panel, shredded into fragments, and classified according to the type of material. Currently, specialized photovoltaic disassembly machines are available on the market, such as one developed by NPC, a Japanese company, which performs a more detailed separation of parts before shredding the waste, thus increasing the material recovery rate (Latunussa et al., 2016).

4. Results and Discussions

The results of the review indicate that, although Brazil is among the countries experiencing the most significant growth in the adoption of solar energy, the absence of a specific policy for the management of photovoltaic PV waste presents a critical challenge to the consolidation of a circular economy within the sector. According to a report by Bio Intelligence Service (2011), the generation of PV panel waste is expected to increase substantially in the coming decades, thereby becoming a relevant issue for solid waste management systems, particularly due to the potential leaching of toxic substances and the loss of scarce metals such as silver, gallium, and indium.

Analysis of the FRELP model demonstrates the technical feasibility of achieving high recovery rates, with efficiencies reaching up to 95% for metals such as silver, copper, and silicon, in addition to 68.6% of the glass and 18.2% of the aluminum present in the modules (Latunussa et al., 2016 However, the same study also highlights significant environmental impacts related to energy consumption and greenhouse gas emissions, particularly during the transportation phases, polymer incineration, and chemical treatment of metals.

The results of the review indicate that, although Brazil is among the countries with the highest growth in the adoption of solar energy, the absence of a specific policy for the management of photovoltaic waste represents a challenge for the consolidation of the circular economy in the sector. According to the International Renewable Energy Agency (IRENA, 2019), the amount of photovoltaic waste could exceed 60 million tons by 2050, with Asia accounting for the largest share of this volume. This scenario highlights the need to anticipate planning actions to avoid environmental and economic bottlenecks.

In the European Union, the inclusion of photovoltaic modules under the WEEE Directive ensured not only mandatory collection but also the creation of infrastructure for specialized recycling (Cucchiella, D'Adamo, and Koh, 2015). This experience demonstrates that regulation can drive both environmental management and new business opportunities in the sector.

From an economic perspective, studies indicate that the recovery value of critical metals, such as silver and indium, could reach 450 million dollars annually by 2030, provided that efficient global recycling systems are implemented (Weckend, Wade, and Heath, 2016). In Brazil, where the recycling structure is still incipient, the adoption of public policies aligned with the concept of a circular economy could contribute to positioning the country within a competitive market for the reuse of strategic raw materials.

Another relevant point is the incorporation of emerging technologies. Recent research highlights that digital tools, such as artificial intelligence and blockchain applied to reverse logistics, can enhance module traceability and reduce operational costs (Zhou, Li, and Zhang, 2022). This trend, still little explored in Brazil, presents great potential for improving the efficiency of the recycling chain.

In the Asian context, China, the world's largest producer of solar panels, faces challenges similar to Brazil with regard to the absence of consolidated regulation. However, pilot projects are already seeking to implement large-scale recycling processes, signaling a movement toward regulatory and technological adaptation (Zeng, Li, and Liu, 2020). These examples demonstrate that emerging countries can build their own solutions, adapted to their realities.

The results of the analysis demonstrate that, despite the advancement of solar energy in Brazil, the absence of specific policies for photovoltaic waste management still represents a significant barrier to the consolidation of a sustainable value chain. International research shows that the improper disposal of modules can generate considerable environmental impacts, particularly due to the potential release of heavy metals such as lead and cadmium, which are associated with health risks and soil and water contamination (Chowdhury et al., 2020). At the same time, studies indicate that the adoption of optimized recycling processes has the potential to substantially reduce greenhouse gas emissions linked to the manufacturing of new modules, thereby contributing to global climate mitigation targets (Xu et al., 2022).

In addition to environmental concerns, the economic dimension also emerges as a strategic factor in the context of photovoltaic recycling. Materials such as silver, copper, and silicon, although representing only a small fraction of the module's total mass, have high added value and can make the process economically viable when reintroduced into the production cycle (Rystad Energy, 2023). It is estimated that the recovery of these elements not only reduces dependence on finite mineral resources but also fosters the development of local supply chains and the creation of green jobs, thereby strengthening the circular economy (Weckend, Wade; Heath, 2016).

However, progress directly depends on the establishment of a robust regulatory framework. The European Union, for instance, has included photovoltaic modules in the Waste Electrical and Electronic Equipment (WEEE) Directive, setting mandatory recycling targets and mechanisms for shared responsibility. Brazil, in turn, still lacks sector-specific regulations, relying solely on the National Solid Waste Policy, which, while providing general guidelines, does not address the specificities of the solar sector (Brazil, 2010; Dias et al., 2023). This misalignment highlights the urgency of more targeted public policies capable of integrating the principles of the circular economy with the realities of national reverse logistics, ensuring both environmental benefits and economic competitiveness on the international stage.

The findings further suggest that, despite the current lack of specific regulations governing the disposal of PV modules in Brazil, there are concrete opportunities to proactively address future scenarios involving waste accumulation. The analysis emphasizes that glass, representing approximately 70% of the total mass of a panel, should be regarded as a key entry point for establishing the economic viability of the recycling chain, given its capacity for indefinite reuse without loss of quality (Feve, 2019).

An additional noteworthy finding concerns the adoption of emerging technologies, such as automated disassembly systems and blockchain-based digital traceability platforms, which have the potential to significantly enhance the efficiency of reverse logistics operations and reduce associated transportation and sorting costs (Li et al., 2024). Furthermore, the implementation of regional recycling models, through the decentralization of treatment centers, could contribute to the reduction of emissions linked to waste transport. It could also promote stronger alignment with state-level solid waste management policies (Dias et al., 2023). These findings suggest that, by adapting international models such as FRELP to the framework established by the National Solid Waste Policy (PNRS), Brazil is well-positioned to develop a sustainable and innovative reverse logistics system for the photovoltaic sector.

These impacts may be further mitigated through the regionalization of reverse logistics efforts, involving the establishment of decentralized sorting and disassembly facilities to reduce transportation distances associated with module handling. Moreover, advanced technologies, including sensor-based tracking systems, blockchain infrastructure, and collaborative digital platforms, can contribute to the optimization of logistical flows and enhance transparency across the entire process, as proposed by Li et al. (2024) in a recent study on next-generation PV recycling networks.

According to Latunussa et al. (2016), the lack of life cycle data and the absence of public policies focused on the end-of-life management of PV modules hinder the implementation of effective recycling strategies. The authors emphasize that the establishment of specific regulatory standards and government support is essential for the environmental and economic viability of photovoltaic recycling.

In accordance with the Ministry of the Environment (Brazil, 2011), reverse logistics systems in Brazil may be implemented through legal instruments such as sectoral agreements, specific regulations, and terms of commitment, with the active involvement of managing entities responsible for coordinating the system, collecting relevant data, and continuously improving the mechanisms for waste return and reuse.

Table 2 presents the materials currently covered by operational reverse logistics systems in Brazil, along with the entities responsible for their management and the primary regulatory instruments employed in their implementation. The activities of these institutions sometimes predate the formalization of sectoral agreements or terms of commitment because earlier legislation, before the establishment of the PNRS, had already mandated the recovery of specific types of waste (Abrema, 2024).

Table 2 – Summary of materials with reverse logistics systems in Brazil.

No.	Material Type	Responsible Institution / Entity	Regulatory Instrument	Year of the Instrument
1	Pesticides, their residues and packaging	inpEV	Decree nº 4.074	2002
2	Lead acid batteries	IBER	Sector agreement	2019
3	Electronic devices and their components for domestic use	Abree Green Eletron	Sector agreement	2019
4	Steel packaging	PROLATA	Term of commitment	2018
5	Glass packaging	Circula Vidro	Decree nº 11.300	2022
6	Packaging in general	Diversas Entidades*	Sector agreement	2015
7	Lubricating oil packaging	Instituto Jogue Limpo	Sector agreement	2012
8	Used or contaminated lubricating oils (OLUC)	ANP Instituto Jogue Limpo	CONAMA Resolution nº 362	2005
9	Fluorescent, sodium and mercury vapor and mixed light lamps	Reciclus	Sector agreement	2014
10	Aluminum beverage cans	Recicla Latas	Term of commitment	2020
11	Medicines, their waste and packaging	GAP	Decree nº 10.388	2020
12	Cells and batteries	Green Eletron	CONAMA Resolution nº 401	2008
13	Waste tires	Reciclanip	CONAMA Resolution n° 416	2009

*Reverse logistics of packaging, in general, involves several entities responsible for collecting information on the functioning of the system.

5. Conclusion

The research highlighted that the rapid expansion of photovoltaic solar energy, while representing a positive milestone in the energy transition, brings with it the challenge of sustainably managing the waste generated at the end of the modules' useful life. A comparative analysis of international models, such as the European FRELP, demonstrated that it is possible to achieve high recovery rates of materials, especially glass, silicon, and precious metals, significantly reducing the environmental impacts associated with improper disposal.

In the Brazilian context, the lack of specific regulation was identified as a future risk, but also as an opportunity for the country to structure public policies aligned with the National Solid Waste Policy (Law No. 12.305/2010). Among the most relevant findings, the centrality of glass as a key element to economically enable photovoltaic recycling stands out, as well as the potential adoption of emerging technologies, such as automated disassembly machines and digital traceability systems, which can make reverse logistics more efficient.

It is therefore concluded that the adaptation of international practices to the national context, combined with the decentralization of recycling centers and the promotion of circular economy principles, can strategically position Brazil within the global energy sustainability landscape. This study contributes to advancing the discourse on regulatory and technological solutions applicable to the Brazilian context, offering valuable insights for the formulation of public policies and the development of future research aimed at establishing a robust and innovative reverse logistics system for photovoltaic modules.

In summary, Brazil has favorable conditions to establish a sustainable photovoltaic recycling chain, provided that specific public policies and incentives for research and development are implemented. The integration of circular economy principles, reverse logistics, and environmental regulation represents a strategic pathway to transform the challenge of solar module disposal into an opportunity for technological innovation, job creation, and the strengthening of the renewable energy matrix.

From a prospective perspective, if consistent public policies focused on the reverse logistics of photovoltaic modules are adopted, it is possible to project the development of a solid recycling market by 2035, capable of recovering critical materials and reducing dependence on imports. Furthermore, the incorporation of technological innovation and environmental education may broaden social benefits, fostering the creation of qualified jobs, the inclusion of waste pickers' cooperatives in high-value chains, and greater transparency in waste flows.

In this context, solar module recycling should not be regarded merely as an environmental challenge but as a driver of sustainable development, industrial innovation, and strategic competitiveness, consolidating Brazil's role in the global energy transition.

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