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# Circularity Options for Photovoltaic Panels at the End of Useful Life

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**Abstract:** Solar panels, when they reach the end of their useful life, can represent a source of hazardous waste if not properly managed. Despite the significant benefits in terms of scalability from the expansion of solar energy generation, there is a risk that these panels will become waste that is harmful to the environment. In Brazil, the installed capacity of photovoltaic energy has already reached around 23.9 gigawatts (GW) and this capacity is expected to increase even further in the coming years. In this context, the objective of this research was to address, through a literature review, circular alternatives for the environmentally appropriate disposal of waste from photovoltaic panels. The analysis revealed that, despite the various circular options explored, such as repair, resale and reuse, Brazil currently only adopts the recycling alternative at the end of the panels' life cycle. This opens up space for future investigations aimed at improving the management of this waste, the valorization of its components, as well as the reduction of its disposal in landfills.

**Key words:** photovoltaic panels, waste management, environmental impacts

## 1. Introduction

The Brazilian electrical matrix is predominantly composed of renewable sources, such as hydroelectric, wind, solar and biomass, and although the predominance of water sources is considerably relevant, their participation in total production has been decreasing, thus, other renewable sources have been gaining prominence, such as solar energy [1].

Photovoltaic solar energy is increasingly advancing in Brazil. According to data from the National Electric Energy Agency (ANEEL), this type of electrical energy has grown, in the last 7 years, by an average of 151% per year. Even with all this expansion, it is still a market that can be further explored, as it is relatively new in Brazil [2].

Solar energy has been breaking generation records in Brazil in 2022. The source grows year after year, despite still representing a minority portion of the country's energy matrix. A clean and renewable source, and therefore strategic in processes of reducing gas emissions that contribute to climate change, solar energy generation is relatively recent in Brazil, and gained momentum from 2010. It is divided into two types: centralized, linked to large plants, and distributed, related to small units such as houses with photovoltaic panels on the roof [3].

Photovoltaic solar energy has just reached 23.9 gigawatts (GW) of installed capacity in the country, surpassing wind energy, which registers 23.8 GW, reports the Brazilian Association of Photovoltaic Solar Energy (ABSOLAR). The great boost from the source of energy generated by the sun has been given by Distributed Generation (GD), an electrical energy generation system installed on roofs, companies and land, and which has a deadline to take advantage of benefits carried since the beginning of the source's implementation in Brazil, in 2012, such as the non-charging of the transmission service by distributors. "Technology helps to diversify the country's electrical matrix, increase supply security,

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reduce pressure on water resources and protect the population against further increases in electricity bills", states Rodrigo Sauaia, president of Absolar, in a statement." [4].

Photovoltaic energy is seen as a promise in terms of renewable energy, as its generation depends only on the incidence of sunlight and the photovoltaic plate [5]. Solar energy comes from a clean and renewable source, however, the equipment used to produce electrical energy through the sun to carry out the conversion can cause damage to the environment and human beings, if discarded inappropriately, as they contain metals heavy in its composition [6].

Photovoltaic (PV) panels are energy sources without fuel costs, however, with relatively high production costs and are manufactured with materials that are exhaustible and environmentally unsafe. Some aspects related to sustainability must be considered, such as cost, resource availability and environmental impact [7].

Studies on the useful life and obsolescence of the system predict a large number of obsolete panels in the next decade [8, 9] (Fig. 1). Therefore, even though photovoltaic panels have an average useful life of 25 years [8], there is time to propose alternatives, predict and manage the environmental impacts caused by the end of life of photovoltaic cells, components of complex recycling and reuse. Furthermore, thanks to the advancement of the sector in Brazil, the management of this end-of-life product is a field of research that still demands development at a national level.

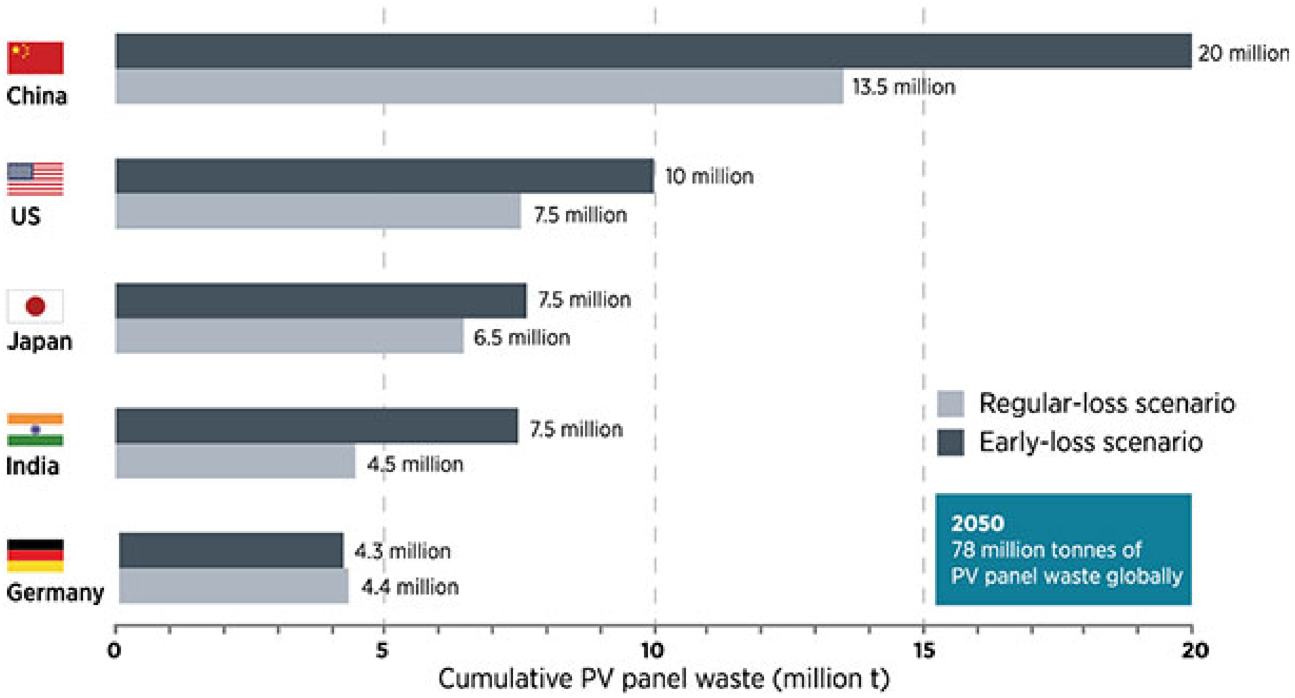


**Fig. 1 Cumulative waste volumes of PV panels by 2050, by country [10].**

While we increase waste generation, solid waste management in the country still remains critical, with a large deficit. Extracting natural resources from one place and burying them in another may seem inefficient from an economic point of view; however, this is what Brazil has been doing with most of its solid waste. The cost is high, not only due to the waste of raw materials, but also due to environmental and public health damage [11].

A crucial solution to face this challenge is the implementation of a Circular Economy (CE) [12]. The integration between solar photovoltaic energy and other renewable energy sources in CE is important for rapid growth and sustainability. Although definitions of CE vary, implementation is the recirculation of materials reaching economic scale, leveraging actions such as reduce, reuse, repair, remanufacture, and recycling [13, 14].

The objective of this article is to raise awareness of the socio-environmental impacts of incorrectly disposing of photovoltaic (PV) panels at the end of their useful life and the proposition of circularity options for PVs seeking to minimize Waste Electrical and Electronic Equipment (WEEE).

## 2. Development

Accelerating the energy transition is an urgent and daunting task. It will require shrewd choices, discipline and thoughtful investments. But most of all, it will require radical action and extraordinary levels of international cooperation [15].

As a consequence of the expansion of the photovoltaic market over the last 20 years, cumulative global photovoltaic waste is expected to grow exponentially. Proper disposal of deactivated photovoltaic panels is crucial to avoid environmental risks and to recover value-added materials [16]. The global amount of photovoltaic waste could reach around 1.7 to 8.0 million tons in 2030 and 60 million tons in 2050, assuming a 30-year useful life of solar panels [17].

The solar cell manufacturing process involves a number of harmful chemicals. These substances, similar to those used in the general semiconductor industry, include sulfuric acid, hydrogen fluoride, hydrochloric acid, nitric acid, 1,1,1-trichloroethane, and acetone. The quantity and type of chemicals used depends on the type of cell and the technology used [18]. One may also find some variability in the use of chemicals to produce the same type of photovoltaic solar cells by different photovoltaic manufacturers. This means that each manufacturer has its own recipe for producing a type of solar cell.

Many hazardous materials, as well as explosive and toxic gases, are involved in the manufacturing processes of thin-film photovoltaic cells and modules. Most of these chemicals are highly toxic and harmful to humans and the environment [19]. According to the literature, PV waste, if not disposed of correctly, can cause the following negative impacts on the environment and human health: a) lead leaching, b) cadmium leaching, c) loss of conventional resources, mainly glass and aluminum, d) loss of rare metals, mainly silver, indium, gallium and germanium [20].

End-of-life (EoL) photovoltaic panels, if not handled correctly during disposal, can pose a threat to human health and the environment [21-23]. Therefore, the disposal of photovoltaic panels will become a relevant environmental issue in the coming decades [24].

The use of valuable resources and the potential for waste generation in the end-of-life cycle (EoL) of photovoltaic technologies has required adequate planning for a photovoltaic recycling infrastructure [25]. To certify the sustainability of PV on large scales of deployment, it is crucial to establish low-cost recycling technologies for the evolution of the PV industry in parallel with the rapid commercialization of these new technologies [24].

As a reflection of the expansion in the use of photovoltaic energy, the recovery of solar panels is not keeping up with the exponential growth in their use. A viable alternative to facing this challenge is the implementation of a CE [12]. In it, processes can be redesigned in order to extend the useful life of materials, reduce environmental impacts and increase financial return [26].

Several studies consider the R structure as the “how to do it” and an inseparable factor of CE [13, 27, 28]. To reflect the hierarchical ambition in the levels of circular strategies, the 10 R's ladder is used to increase awareness that CE is not just related to the recycling of waste streams and that strategies at the top of the pyramid have greater preference linked to smaller environmental impacts, following this hierarchy avoids waste and creates potential value [29] (Fig. 2).


**Fig. 2 Circularity levels: 10 R's [30].**

Following the order of priority, refusal of use must first be adopted, followed by reduction, which implies reducing the amount of material used per unit of product. Next, it is important to rethink the product in terms of its circularity. In addition, options such as repair, refurbishment, remanufacturing and reuse must be considered. Ultimately, recycling materials and resources is an alternative to be explored. However, if there is any waste remaining that cannot be recycled, incineration with energy recovery can be considered, although this practice is not normally adopted within a circular economy [30].

## 3. Material and Methods

### *3.1 Methods*

The research was carried out through a narrative review of the literature. Prodanov and Freitas (2013) [31] define this technique as an investigation of current theoretical sources (articles, books and theses) on the theme that underlies the content, bringing the concepts required in the research. Documents relevant to the topic were sought by searching the Science Direct databases, the Periodicals Portal of the Coordination for the Improvement of Higher Education Personnel (Capes) and the Research Gate platform.

## 4. Results and Discussion

### *4.1 Results*

In July 2012, the European Union officially revised the WEEE directive, adding photovoltaic components as discarded electronic devices so that they are included in the ten WEEE categories. From now on, solar photovoltaic elements will be included in the electronic waste management system and must be collected and recycled [20, 32].

The cycle typically begins with mining materials from the ground and continues with the processing and purification of materials through to the manufacture of compounds and chemicals used in processing and manufacturing, transportation, installation, use, maintenance and eventual decommissioning and disposal and/or recycling. As materials are reused or recycled at the end of their first life into new products, the structure is extended from "cradle to cradle" [7].

According to Jayawardena et al. (2019) [33], the photovoltaic cells that have been developed to date can be classified into 4 main categories called generations (Table 1).

### *4.2 Discussions*

The first mentionable quantities of end-of-life PV will occur around 2025/2030 (188 and 2.03 MW respectively), reaching around 68,000 MW in 2050. The future outcome of current research, development and testing of PV and new recycling techniques is difficult to project. Emerging technologies may allow for a lower content of hazardous substances and will require new types of recycling processes [20].

The increasing waste of PV is an environmental obstacle to be overcome, but it also opens up a range of opportunities to create processes that can transform this discarded material into an economic and ecological solution. For this to happen, there must be adequate end-of-life (EoL) technologies and management policies for photovoltaic systems and, particularly, photovoltaic modules [10].

**Table 1 Evolution of photovoltaic cell generations [33].**

| Generation | Categories |
|---|---|
| First | It is based on crystalline, monocrystalline and polycrystalline silicon technologies, and gallium arsenide (GaAs). |
| Second | It includes amorphous silicon (a-Si) and microcrystalline silicon (μc-Si) thin-film solar cells, cadmium telluride/cadmium sulfide (CdTe/CdS), and copper, indium, gallium (CIGS) solar cells. |
| Third | It involves newer compound-based technologies including nanocrystalline films, active quantum dots, tandem or stacked multilayers of inorganic materials based on III-V materials such as GaAs/GaInP, organic solar cells (polymers), dye-sensitized solar cells, etc. |
| Forth | Also known as "inorganic-in-organic", it combines the low cost/flexibility of polymer thin films with the stability of new inorganic nanostructures, such as metal nanoparticles and metal oxides or organic-based nanomaterials, such as carbon nanotubes, graphene and their derivatives. |

According to the life cycle analysis carried out by Gertsakis and Lewis (2008) [34], there are four different EoL approaches for PV modules: reuse, recycling, incineration and landfill. Each approach has particular characteristics and can offer a different improvement in photovoltaic modules in relation to the overall environmental impact. Only reuse and recycling approaches can be considered circular. Reuse is also a popular choice in the waste management hierarchy, and, for photovoltaic modules, this involves repair [35].

Improving solar modules is feasible depending on the conditions of the materials. Typically, module repair processes involve applying a new aluminum frame or replacing the junction box. It can also be a solution to replace diodes, plugs, sockets and much more [15].

In recycling, different processes are being developed for all photovoltaic technologies. Several techniques can be used at this stage [15], including thermal [36, 37] and chemical (organic and inorganic) [38-40] and mechanical recycling process [41].

Incineration of solar modules, like electronic waste, in general, is harmful to the environment due to the release of toxic heavy metals, such as lead, into the atmosphere. Another linear approach that should be avoided is landfill disposal, in most cases, before going to landfill, the photovoltaic module is separated from the balance of system (BOS), which allows you to separate the specific components, based on their types of waste. BOS refers to the non-modular components of a photovoltaic system, including inverters, racks, cables/wires, switches, cabinets, fuses, ground fault detection [34].

Today, most EoL modules are disposed of in landfills, mainly because photovoltaic module recycling processes are not yet economically viable and regulations in most countries are not yet well established [42]. Currently, there are not enough policy indications to deal with these problems.

According to Ovaitt et al. (2021) [43], PV can follow different circularity options (Table 2).

When a solar system reaches the end of its useful life, actions must be taken to maximize the reuse of the materials present in it, as it continues to be a product with excellent added value, from which many uses can still be extracted. Around 96% of a photovoltaic module has recyclability potential (ABSOLAR, 2023) [44].

In Brazil, the circularity of these materials can be observed in the activities of companies such as SunR, the first organization specialized in this segment. SunR offers its customers and partners a certification seal. This seal certifies the client to companies, inspectors and investors, of the environmentally correct disposal of electronic waste from the photovoltaic sector for recycling (SUNR, 2023) [45].

**Table 2 "R" circular options [43].**

| Circular option | Definition |
|---|---|
| Recycle at the manufacturing stage | Pre-consumer, industrial scrap recycling. Material enters this recycling cycle due to manufacturing inefficiencies. |
| Repair | A module has failed and an in-place fix for the module defect or problem is possible. If the module is not repaired, it is assumed to be at EoL. If the module is repaired, it continues to generate energy. |
| Resale or refinance | System owners agree to produce power for a certain period of time through a Power Purchase Agreement (PPA) or other contractual mechanism. After the PPA expires, the owner may choose to keep the system operating beyond the module warranty or project financing period if it is still economically viable. System owners continue to sell energy from the system or sell the system. This represents the real-world use case of PV systems being sold to continue operation after the end of a PPA, as well as sales of individual modules on the secondary market. |
| Reuse | The module is in EoL (due to degradation or end of the project) and is dismantled and removed from the field. Externally, the module is evaluated/tested/recertified and found to be in acceptable working condition to be sold on a secondary market (perhaps as a spare for a similar system) and is subsequently installed in a new location. |
| Recycle at end of life (EoL) | When a module is at EoL and is not reused, repaired, refurbished, or sent directly to a landfill, it can be recycled into its constituent materials. High-quality recycled materials can replace virgin materials in the manufacture of new modules or other products (e.g., flat glass for container glass). Low-quality recycled materials can be recycled into other products with less stringent material quality requirements. |

In general, in the recycling procedure, initially, the company collects unusable solar panels. Subsequently, dismantle the panels. During this stage, aluminum, glass, polymer and a combination of metals are removed. The aluminum is sent to the foundry industry. Glass, which can make up at least 70% of the composition of a plate, can be transformed into microspheres used in highway lighting. Plastic and other materials such as metallic mixtures: silicon, silver, copper and tin, also receive different appropriate treatments and are reused as secondary raw materials for new materials. Considering the circularity options proposed by Ovaitt et al. (2021) [43], the only one that cannot be applied in Brazilian territory is the first, which is recycled at the manufacturing stage. This option becomes unfeasible due to the fact that we do not have manufacturers in terms of primary materials for solar panels in the Brazilian territory, making it impossible to reinsert recycled materials into the production chain itself (ABSOLAR, 2023) [44].

## 5. Conclusions

Based on the growing expansion of the use of solar energy, as well as its installed photovoltaic generation capacity and considering the increase in waste generation from this activity, the study presented circularity options that aim to recover resources, extend their lifespan, waste minimization, which represent a substantial positive impact on the environment.

The study shows that despite the various circular options explored, such as repair, resale and reuse, our country currently only practices the alternative of "recycling at the end of the life cycle" of panels. Future investigations are suggested to improve the management of this waste, the valorization of its components, as well as the reduction of its disposal in landfills.

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