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Review Article

Photovoltaic electronic waste in Brazil: Circular economy challenges, potential and obstacles

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ABSTRACT

Photovoltaic (PV) energy production is a promising and mature technology for producing renewable energy. By contrast, solar panel disposals can generate problems for waste management, given that the amount of PV solar energy e-waste is more significant than other types of e-waste, given that this waste contains abundant metals and toxic materials, and given that this energy is being increasingly used. Local solutions need to be discussed and evaluated so that the PV industry can provide sustainable renewable energy. This paper discusses the environmental impacts of PV solar energy and PV panel recycling in Brazil. More efficient technological solutions and process developments will be needed to adequately treat problems arising at the end of the useful life cycle of PV systems. However, more than these technological solutions and process developments are required. Political mechanisms and regulatory structures will also need to be developed and implemented at the end of the life cycle stage to prepare, encourage, and develop appropriate industrial waste treatment applications. The advent of sector agreements for electrical and electronic equipment in Brazil has partially dealt with these waste problems. Sector agreements list equipment and devices that must have defined reverse logistics systems.

1. Introduction

As society works towards reducing its dependence on fossil fuels, renewable energy demands have grown rapidly over recent years. Photovoltaic (PV) solar energy is a renewable energy source that has seen expressive growth in recent decades (Mathur et al., 2020). PV energy production is one of the most promising and mature technologies for producing renewable energy. PV technology is environmentally friendly and is a popular way of generating energy (Chowdhury et al., 2020).

While there are huge benefits that come from the growth of solar power generation, the end-of-life phase for solar panels can result in hazardous waste generation. Global PV capacity reached around 400 GW at the end of 2017, and this is expected to increase further to 4,500 GW by 2050. An average PV panel has a 25-year lifespan. Thus, worldwide waste production is expected to reach between 4% and 14% of this total generation capacity by 2030 and to increase to over 80% (about 78 million tons) by 2050 (Chowdhury et al., 2020).

Technological advancements in the electronics industry, and accelerated PV power deployments, have resulted in high demand for metals and raw materials for PV production. The amount of solar PV e-waste is comparatively higher than other e-waste, given the abundance of metals and toxic materials present in the panels, causing problems for solar PV e-waste disposals (Gautam et al., 2022).

Material extractions, waste treatment requirements, options for recovering high purity secondary resources, and impacts on all sustainability dimensions need to be evaluated and optimised so that the PV industry can both provide sustainable renewable energy and facilitate decarbonisation (Bartie et al., 2021).

Farrell et al. (2020), state that adopting Circular Economy (CE) principles can help offset environmental factors like manufacturing emissions and increase recycling and recovery rates. Effective methods for managing this waste must be developed and implemented to prevent large volumes of hazardous waste from being disposed of in landfills. PV waste can also be seen as a potential source of valuable materials, given that it contains various materials that can be recovered (Ardente et al., 2019; Mathur et al., 2020).

The amount of PV panel waste is expected to grow exponentially in the coming decades. However, few studies have analysed how this waste can be specifically recycled (Ardente et al., 2019; Gautam et al., 2022;

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Mahmoudi et al., 2021).

A study by Ardente et al. (2019) analysed the performance of different crystalline silicon PV waste recycling processes from a life cycle perspective. They compared the life cycle impacts of recycling to environmental benefits from recovering secondary raw materials under different scenarios. High-efficiency recycling can meet these goals, allowing high-quality materials like silicon, glass, and silver to be recovered, often lost in standard recycling procedures. The benefits of recovering these materials offset the impacts of high-efficiency recycling processes.

A study by Mahmoudi et al. (2021) discussed the environmental impacts of recycling PV panels and stated that Australia will face severe critical PV end-of-life management challenges from the early 2030s onwards, given the widespread deployment of PV panels there over the last two decades.

Gautam et al. (2022) studied India and proposed developing an organised recycling infrastructure there for PV solar panel waste. The study states that small and medium-sized companies play an essential role in applying CE principles to e-waste.

Given this context, this article discusses the scenario and impacts of photovoltaic solar energy and the recycling of photovoltaic panels in the Brazilian context, since this is a topic of concern in the pioneering regions of this type of technology, but with still incipient discourse in Brazil, but which deserves a closer look by the authorities and society for the proper negotiations, with the implementation of public policies and taking advantage of opportunities will be generated, since the negotiations for the management of the end of life of photovoltaic modules, in the vast majority of countries, still require technological and regulatory actions that must be well integrated so that they can have the expected effects. Exception of Europe, the other regions of the world are still quite incipient regarding this topic, Komoto and Lee (2018).

2. Method

The study aims to discuss the environmental impacts of PV solar energy and PV panel recycling in Brazil with the support of circular economy-inspired concepts. It is a described and qualitative study that discusses Brazil's circular economy challenges, potential and obstacles.

In constructing this literature review, databases such as Web of Science and ScienceDirect were primarily used to obtain literature. As Photovoltaic electronic waste is an issue concerning also industry, some literature was used in governmental, agency and sector reports (International Energy Agency, International Renewable Energy Agency, National Electric Energy Agency, Brazilian Association of Public Cleaning and Special Waste Companies, Brazilian Energy Research Company, European Commission and Energy Information Administration).

3. PV solar energy growth

PV solar energy has low maintenance rates and is highly reliable and is thus considered a green source of energy, with a strong positive ecological "footprint" since this technology contributes to reducing greenhouse gas (GHG) emissions (Lira et al., 2019).

Excessive fossil fuel consumption has led to significant environmental impacts. Environmental issues associated with electricity costs have boosted PV solar energy growth worldwide (Xu et al., 2018). Data from International Energy Agency ((IEA 2020)), highlights the growth rates of renewable energy worldwide. We can see that PV solar energy has an average annual growth rate at about 36% from 2000 on (Fig. 1).

According to the International Renewable Energy Agency (IRENA, 2022), in 2021, the total worldwide installed PV capacity was 843.08 GW, corresponding to about 27.5% of the total installed renewable energy capacity. More recent data from IRENA on PV generation worldwide comes from 2019, when approximately 678.9 TWh of energy was generated using PV power, corresponding to 9.8% of all renewable energy generated worldwide during this period (Fig. 2).

It is estimated that in 2050 electricity generated from PV power will reach values ranging from 7,160 TWh to 22,716 TWh (depending on the scenario), which would represent up to 20% of the world's total electricity generation (IRENA, 2021; EIA (2019).

Some questions naturally arise following from all this growth, i.e., how will all of this PV waste be disposed of when current and future systems reach the end of their useful lifespans. In general, Photovoltaic System Waste (PVSW) comprises basically the same constituent elements as Electrical and Electronic Product waste (WEEE). However, because PV panels comprise more than 80% of any given solar generation system, the proportion of constituent elements like the glass surrounding and encapsulating the PV cells can differ greatly from WEEE.

The materials that comprise the panels cause the same effects as WEEE to living beings and the environment. Table 1 summarises the

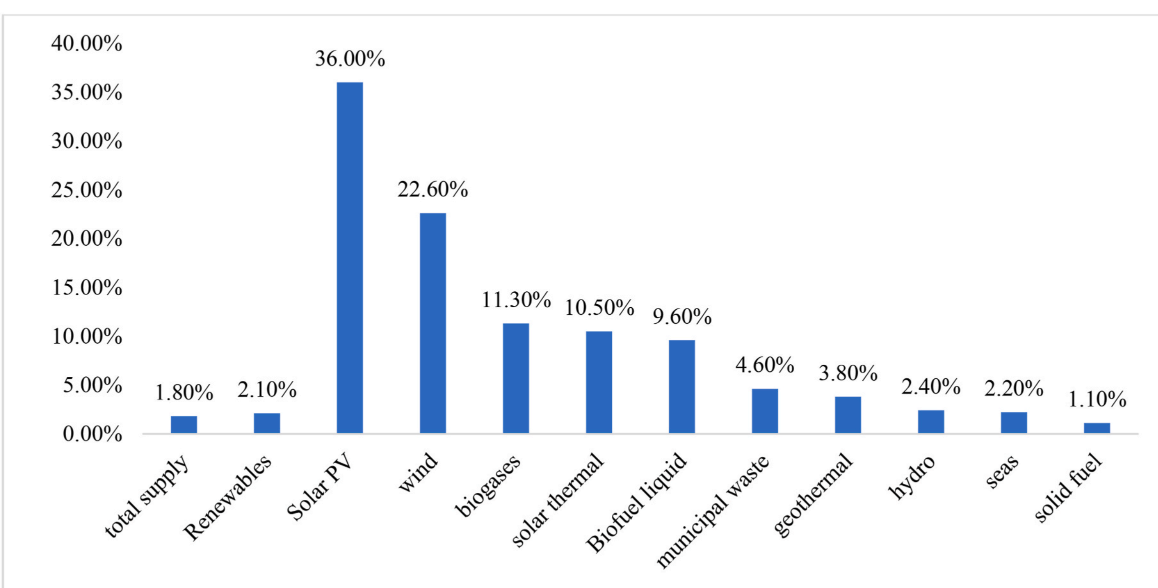

Fig. 1. Annual PV growth rate, 1990 to 2019 per type of renewable resource.
Source: The authors of this study used IEA data (2020)

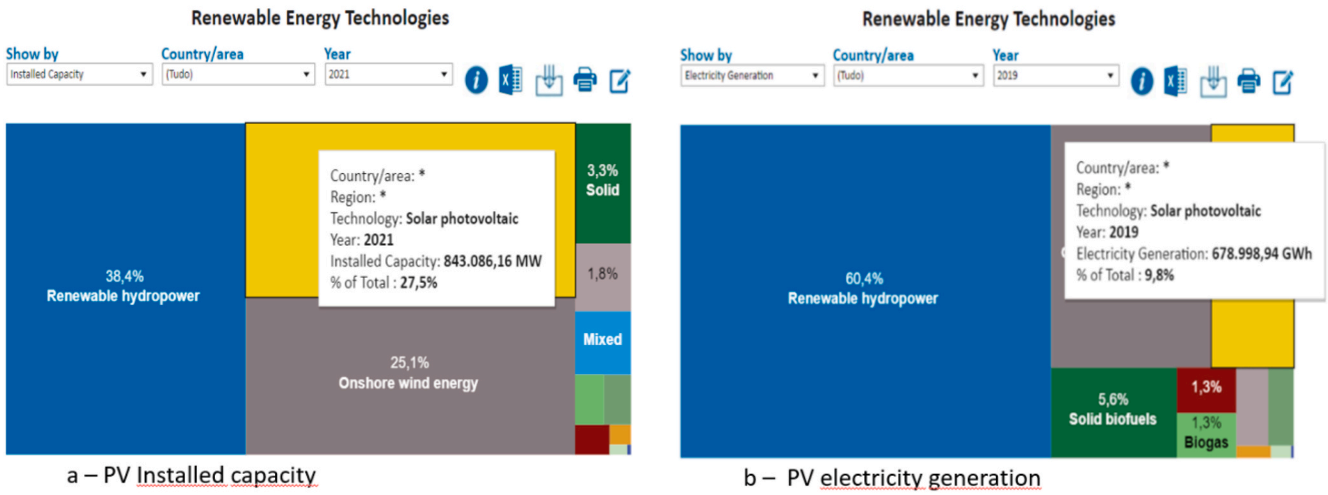

Fig. 2. Worldwide PV power installed capacity.

Table 1
Constituent materials in a typical crystalline silicon panel.

Material	Percent
Glass, containing antimony (0.01–1% kg of glass)	70.00%
Aluminum	18.00%
Cables (containing copper and polymers)	1.00%
Polymer-based adhesive (EVA) encapsulation layer	5.10%
Back-sheet layer (polyvinyl fluoride)	1.50%
Solar cell, containing silicon metal	3.65%
Silver	0.053%
Internal conductor, aluminum	0.53%
Internal conductor, copper	0.11%
Other metals (lead, cadmium, tin, etc.)	0.053%

Source: Adapted from Latunussa et al. (2016)

constituent elements of typical PV panels based on crystalline silicon.

Thus, there will invariably be increased waste generation with increased PV demand. Dias et al. (2016), state that the amount of WEEE generated worldwide has been underestimated since there are no accurate methods for determining the total amount of WEEE discarded worldwide. However, PVSW waste can be determined more efficiently based on how these systems are implemented, e.g., in Brazil, where all systems legally connected to the grid are registered with ANEEL, similar to what is done worldwide.

Komoto and Lee (2018) emphasise that development strategies for managing system life cycles will establish more reliable future projections on the actual amounts of generated PVSW which will serve as a basis for dealing with problems posed by Dias et al. (2016), relative to PVSW applications. However, if actions are not taken to develop strategies, as per Komoto and Lee (2018), future PVSW waste scenarios could be quite harmful to the environment, constituting a serious threat to human health (Li et al., 2022). Inadequate PVSW disposals could include a serious problem for regions where PV systems are employed.

Some problems caused by inadequately disposing of PVSW waste include: leaching chemical elements that are dangerous to living beings, e.g., lead and cadmium, and rare metal losses, e.g., silver, indium, gallium, germanium, and palladium, and losses of other recoverable materials that are not as rare, but that still have economic value, e.g., aluminum, silicon, and glass (Xu et al., 2018). The precious metals in PVSW require special handling and specific recycling methods. These elements are present in low concentrations in PV systems, making a recovery very difficult. The challenge is how to manage these issues since PV volumes are growing exponentially. With installed capacities already at more than 800 GW today, the International Energy Agency estimates there will be 4675 GW of installed capacity by 2050 (Komoto & Lee, 2018). In a zero-carbon scenario (IEA, 2021a), however, installed capacities could exceed 14,000 GW by 2050.

Sharma et al. (2019), show two scenarios for generating PVSW residue. One scenario considers a regular life cycle, with no premature equipment losses, while the other scenario considers premature equipment losses, which can occur due to various factors, e.g., transportation, premature failures, or system operation losses caused by environmental issues.

PVSW waste generation under regular scenarios for 2030 is estimated at 1.7 million tons and 60 million tons by 2050. For scenarios with premature losses, estimates range from 8 million tons in 2030, to 78 million tons in 2050. These numbers, in fact, vary between these ranges for any future scenario with little variation to current practices.

Sharma et al. (2019), gave a loss scenario for 2050 resulting in 78, 000,000 tons of waste considering the percentage mass of rare and hazardous materials like silver and other metals like cadmium, lead, tin, etc. as presented by Latunussa et al. (2016) (Table 1), for crystalline silicon PV modules, equivalent to 82,680 tons of PVSW waste per year, for cases without proper management (Table 2).

Given this situation, there is an opportunity for developing potential markets for transporting, packaging, repairing, reusing, recycling, etc. PV systems at the end of their useful lifespans. More efficient plants and technological processes that can expand processing capacities and segregate product quantities are requirements for this new market.

Recent regulations on PV panel end-of-life management in most countries still need integrated technological and regulatory actions to reach their expected effects (Komoto & Lee, 2018; Sharma et al., 2019). Currently, only 10% of all PV panels are recycled worldwide. This is because there are regulatory gaps in the sector (Lunardi et al., 2018, chap. 2). With the exception of Europe, with its Waste Electrical and Electronic Equipment (WEEE) directive, revised in 2012 to include PV panels, other regions are behind on this topic, since PV waste is treated either as common solid waste, or normal electronic waste in most regions, or worse, there is no treatment at all.

Table 2
Rare or hazardous material annual disposals by volume.

		PVSW volume in 2050 in tons (t)	Bulk amount of rare and hazardous material that discarded per year in (t)
% mass of silver	0.053	78000000	41340
% mass of other rare or hazardous metals	0.053		41340
% total	0.106		82680

PVSW was added to the list of waste categories in the European WEEE directive, expressing how manufacturers and importers need to collect and recycle discarded PV generation systems (Xu et al., 2018). This framework has already been included in Germany and the United Kingdom. Some states in the U.S.A., have made movements in this direction, along with Japan, although to a lesser degree, the latter giving greater emphasis to developing technologies for treating PVSW (Sharma et al., 2019).

4. PVSW in Brazil

In Brazil, solar energy capacity went from 13 MW in 2013 (IRENA, 2022) to 16.317 GW in 2022, with 5.318 GW coming from centralised generation and 10.999 GW coming from Distributed Generation (DG) up to June 2022 (Fig. 3).

Future estimates for Brazil are not always accurate regarding some socioeconomic aspects. According to data from the Ten-Year Energy Expansion Plan (PDE 2029) from the Brazilian Energy Research Company (EPE), Brazil reached 2029 expected levels ahead of time in 2022 and overcame the 10 GW PV DG installation barrier (EPE, 2020). Political, technical, environmental, and economic aspects and financial crises or health crises significantly alter future estimates. Thus, it would be more prudent to select a range of estimated future values.

According to estimates from the National Energy Plan 2050 (PNE) by the Brazilian Energy Research Company, Brazil will reach between 27 and 90 GW of installed PV generation capacity by 2050 (5%–16% of the total installed capacity in Brazil), depending on restrictions, for centralised generation alone, i.e., not considering residential or commercial installations (EPE, 2020b).

However, the National Electric Energy Agency (ANEEL) website shows in Fig. 4 that there is around 60.052 GW of installed power as of this study (June/2022). This is already much higher than estimates from EPE, the most pessimistic scenario for 2050, forecast at 27 GW.

The PNE 2050 does express concern with respect to PVSW recycling. Recommendations for 2030–2040 are directed toward governmental and industrial actions to address regulations for PVSW component recycling (EPE, 2020b).

5. PVSW end-of-life waste characteristics

One needs to know the kind of system in operation to more accurately describe the types of waste generated by PV systems. This could either be an on-grid (connected to the grid) or off-grid (not connected to the grid) system since off-grid systems use batteries as integral system elements in most cases, while on-grid systems do not mandate battery use. Generally, recovered end-of-life PV waste contains valuable components like glass, aluminum, silicon, EVA (polyethene-co-vinyl acetate), and precious or rare metals.

The types of chemical elements in panels change according to the panel's generation. This could vary from first-generation panels to second or third-generation panels. First-generation PV panels basically comprise crystalline silicon modules (c-Si), which are subdivided into monocrystalline silicon (m-Si), and polycrystalline silicon (p-Si) latter being less efficient than monocrystalline silicon. Second generation PV modules comprise thin films of materials based on amorphous silicon (a-Si), cadmium telluride (CdTe), cadmium selenide (CdS), gallium

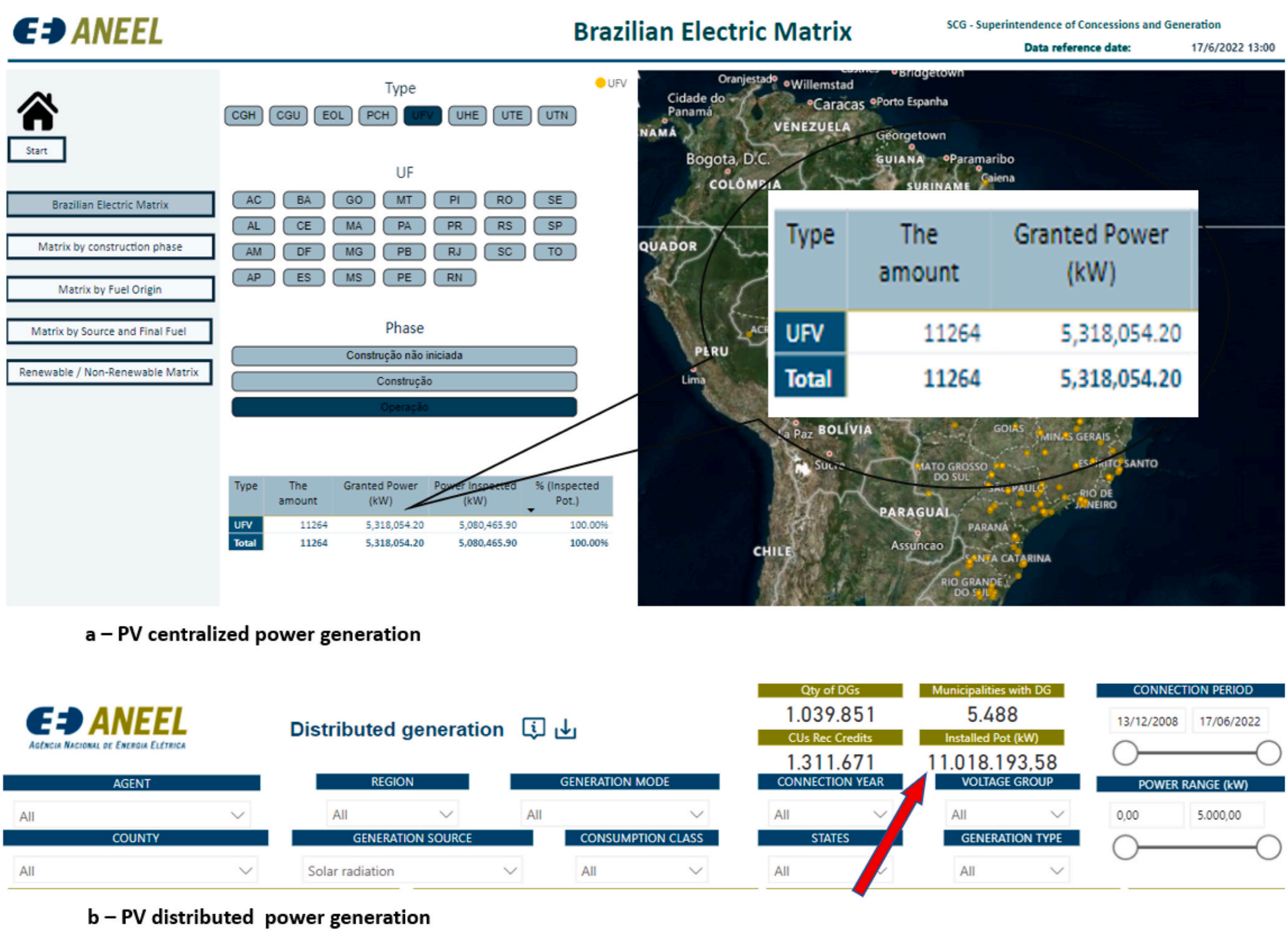

Fig. 3. Installed capacity for centralised and DG PV generation.
Source: ANEEL (2022a, b)

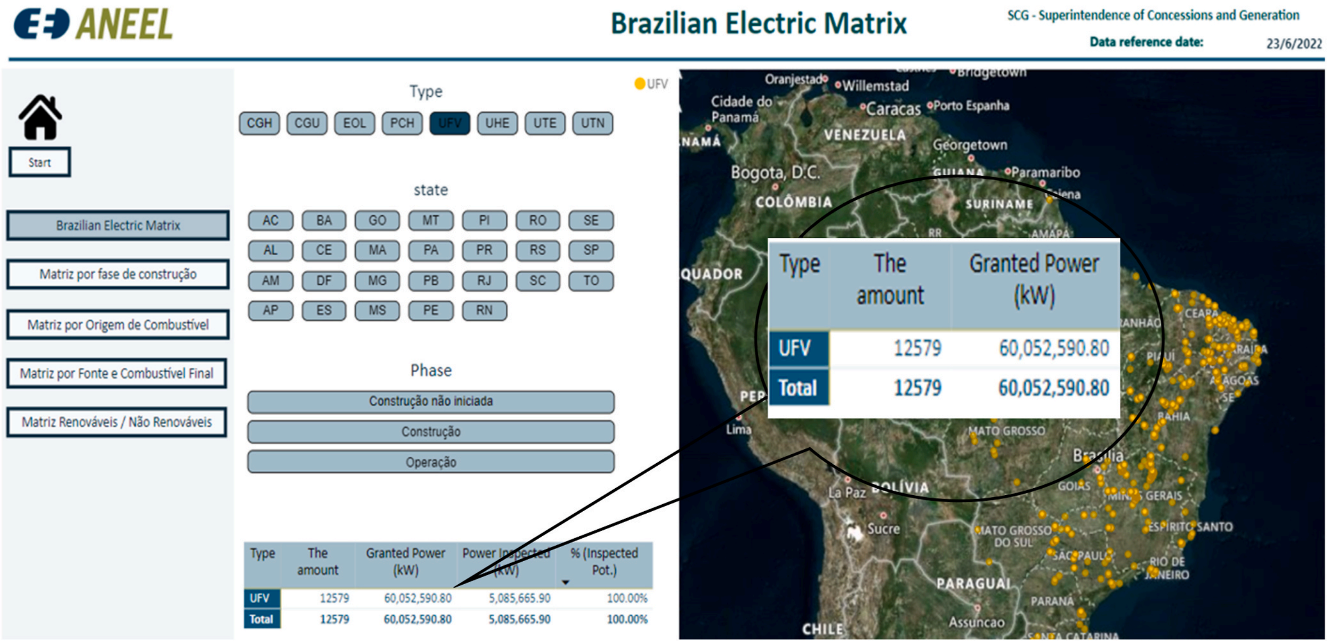

Fig. 4. Current volume of installed PV systems.
Source: ANEEL (2021)

arsenide (GaAs), copper-indium-gallium-selenium (CIGS), and copper-indium-selenium (CIS). Third-generation PV modules comprise sensitised organic dyes or hybrid solar modules, which are still under development, and are not yet competitive in the marketplace.

5.1. *Module waste*

About 90% of all PV panels manufactured worldwide are crystalline or polycrystalline silicon-based modules (Domínguez & Geyer, 2017). However, a study by Mahmoudi et al. (2021), indicated reduced use levels of these materials in the future. Polycrystalline silicon modules account for more than 90% of all modules. Other types of modules currently account for less than 5% of all modules worldwide.

The waste generated by end-of-life PV systems and discarded PV modules is most concerning, primarily due to their volumes. However, system balance elements, i.e., other system components like the inverter, the battery, the electrical material and others, also warrant attention, given their waste characteristics, since the constituent elements in inverters (electronic components) contain rare chemical elements and can also be dangerous to human health.

We should mention that some studies have sought to evaluate the failure modes and degradation forms of PV systems throughout their life cycles (Aghaei et al., 2022; Kim et al., 2021), thus allowing necessary actions to be taken to guarantee performance and reduce losses.

5.1.1. *The frame*

The PV system frame supports the module structure and comprises anodised aluminum, at about 18% of the entire module mass (Latunussa et al., 2016). The aluminum recycling process for the PV system frame has numerous advantages since aluminum recycling is sustainable, and aluminum can be recycled many times without losing its physical properties. More than 90% energy savings can also be achieved compared to the energy consumption needed to produce raw aluminum (Capuzzi & Timelli, 2018).

Additionally, CO2 emissions generated in the aluminum recycling process constitute only 4.6% of the aluminum manufacturing emissions over the entire extraction chain, not to mention the element losses occurring throughout the process (Wong & Lavoie, 2019; Ding, Gao, & Wang, 2012).

5.1.2. *Glass*

Glass does not decompose within human time frames. About 75–80% of the entire PV module mass comprises glass, and glass mass corresponds to the greatest percentage of waste generated by these systems. Recycling or reusing glass would greatly contribute to the environment since glass waste would no longer be sent to landfills, dumps, or improperly disposed of in the form of rubble. Glass recycling would also reduce CO2 emissions since about 86 Mt are produced every year (Westbroek et al., 2021).

Recycling or reusing glass is very advantageous from an economic standpoint since there are up to 30% energy consumption savings when using recycled material (Westbroek et al. al., 2021) by generating services and labour for the glass recycling chain, in the form of collector and recycler cooperatives, for example. Civil construction products like rebar, predate slabs, etc., can be made from reusing discarded PV glass (Ansanelli et al., 2021).

5.1.3. *The encapsulator*

The encapsulator corresponds to 5.1% of the total PV module mass (Latunussa et al., 2016), and encapsulator material degradation is the most significant contributor to photovoltaic module failure (80% system efficiency reductions). Degradation occurs in the function of ultraviolet radiation, causing decreased sunlight absorption as the material acquires a yellowish colour. The encapsulator fixes the photovoltaic cell layers to the module structure and seals and protects the module from environmental weathering.

Removing the encapsulator is the first step in separating and recovering materials. For the most part, EVA is the main material used as an encapsulator, constituting a major problem for separating components and, consequently, subsequent material recoveries (Fiandra et al., 2019). Other materials are starting to be used, like thermoplastic polyurethane (TPU), polyvinyl butyral, thermoplastic polyolefin (TPO), and silicone-based compounds. These perform better compared to EVA, which takes 25–30 years to degrade to 80% in general. Silicone-based encapsulants extend this interval beyond this period, which means increasing the useful lifespan of EVA-based systems in practice. However, high prices and lamination problems have resulted in silicone not being widely accepted in the market (IEA, 2021b), making it hard to use alternative materials to replace EVA as the standard encapsulator for PV applications (Aitola et al., 2022).

One candidate for replacing EVA is thermoplastic polyolefin (TPO). TPO can be produced cheaply and is resistant to failures common to thermoplastic encapsulants (Kempe et al., 2015). Its price and lamination procedures are similar to EVA (Adothu et al., 2019).

Some methods for removing EVA include chemical and physical processes. Chemical processes use dissolution via acids or solvents (Kim & Lee, 2012). Physical processes use pyrolysis decomposition (Dias et al., 2016). It is believed that this method is not still feasible on an industrial scale (Sica, 2018; Kim & Lee, 2012), given the difficulties of eliminating chemical products, the need for treating toxic gases, and the high levels of required energy. Thermal processes are more viable than chemical processes, even though they result in environmental problems (Strachala et al., 2017). In practice, there is no single method for separating, treating, and recovering encapsulator materials, since processes depend on the module type that will be processed (Duflou et al., 2017). The physicochemical characteristics of the modules also influence the process efficiency and the environmental liabilities during heat treatments.

5.1.4. Silicon

PV module recycling processes are not very profitable since they mostly focus on recovering aluminum, glass and copper (D'Adamo et al., 2017), and this ends up negatively influencing PV waste collection and treatment (Ardente et al., 2019). One way to boost profitability is by increasing rare and noble material recoveries, like silver and silicon (Komoto & Lee, 2018). Around 235,000 tons of silicon waste are expected to be produced by 2030 in the European Union alone (EC, 2017).

Given the data, more efficient module recycling processes need to be developed. However, global recycling rates using traditional processes in western Europe are around 24%, well below the current minimum targets of 80% (in mass) for reusing and recycling, as defined by the WEEE Directive. However, technological processes can lead to 83% recycling rates (Ardente et al., 2019). In Brazil, there are no reports of industrial PV module recoveries or recycling because Brazil is in an incipient, albeit accelerated, phase of PV system integration.

5.1.5. Silver

Even though silver is not a significant PV module component by percentage mass, it has significant economic value.

Given its excellent physical characteristics and corrosion resistance, silver is widely used in contact circuits to promote generated electron flows in the semiconductor material (Grandell & Thorenz, 2014).

Silver is a very rare ore found in a few countries. Most of the time, silver is a by-product of other minerals in nature. In Brazil, silver is rarely found in nature.

The amount of silver used in c-Si-based PV modules was reduced from 400 mg to 130 mg between 2007 and 2016, to reduce the width of the metal band and busbar area in the cells. The minimum amount of silver needed to ensure a current within the conductor system is expected to reduce to approximately 65 mg by 2028. However, it is not expected that silver will be replaced as a solar cell conductor over the next decade (IEA, 2021b). Considering the percentage weight mass of silver in PV modules (approximately 0.05%), and considering a forecast of 60–78 million tons of discarded modules in 2050 (Sharma et al., 2019), Dias et al. (2016), state that there is 630 g of silver per ton of crystalline silicon per module on average, equivalent to about 37,800 tons to 49,140 tons of silver that will be discarded if it is not recovered (Farrell et al., 2020).

The constituent silver in the discarded PV module waste needs to be recovered, given these reports, and now there are different technologies for recovering this Silver, and thanks to the price of silver, many companies, mainly in Asia, are also now interested in recovering silver from PV modules and electronic waste in general. In Brazil, there are no industries recovering or recycling silver, and in general, electronic waste is sent abroad to recover rare elements, or waste is improperly disposed of.

5.1.6. Other components

According to Xu et al. (2018), it is perfectly possible to recover and/or recycle silicon and other rare metals contained in PV modules, and so consequently, it is also possible to generate complete economic value chains for all stages of the product's life cycle. There are several processes that can do this, which include using mechanical methods, or chemical processes with acid, alkaline, and organic solvents to remove or dissolve EVA. Fig. 5 shows a simplified process that can be applied to PV modules to recover or recycle its products and elements.

6. The challenges, the potential and the obstacles of circular economies

In Brazil, federal law 12,305 from August 2, 2010, initially regulated by federal decree No. 7,404 from December 23, 2010, established the National Solid Waste Policy (PNRS). This law set up the leading solid waste regulatory framework in Brazil. The PNRS took about 20 years to prepare. Brazil has advanced somewhat relative to its solid waste management since it was implemented, but not as it should have. According to an annual report from the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE), which comprises urban cleaning companies, around 79 million tons of solid waste were produced in 2020 (ABRELPE, 2020). Over ten years, the urban solid waste generation rate grew by 17.9%, practically double Brazil's population growth rate, which was 8.9% during the same period.

According to this same report, there has been a significant increase in selective collection rates over the last few years, from 56.6% in 2010 to 73.1% in 2019. However, there are considerable disparities among various regions. By contrast, over these ten years, there was a very slight improvement in adequate disposal percentage values, as Brazil went from having 56.8% of its Municipal Solid Waste (MSW) correctly disposed of, relative to the 59.5% total generated amount.

The data show that Brazil still needs to evolve its MSW management practices in many respects, especially because MSW is only a portion of the entire volume of generated solid waste, according to Art. 13, item I in law 12,305/2010 (Brazil, 2010).

Law 12,305/12 established sector agreements as a PNRS instrument to establish ways of environmentally and adequately disposing of solid waste using reverse logistics and to establish sustainable consumption practices by bringing manufacturers, importers, traders, distributors, and consumers together. Currently, a series of sector agreements are in effect that allows a series of products to be collected after their life cycles have expired via reverse logistics processes (Fig. 6). These products include batteries, aluminum cans, tires, steel packaging, lubricating oils, packaging, medicines, lead acid batteries, electronics, electronic components and others. Electronic components are regulated by the Ministry of the Environment, and the Brazilian Association of Electrical and Electronics Industries (ABINEE), which represent electrical and electronic equipment manufacturers listed in the agreement, which include the Brazilian Association of Information Technology Products and Services (ADRADISTI), the Federation of Associations of Brazilian Information Technology Companies (ASSEPRO), the Management Agency for National Electrical and Electronic Equipment Waste (GREEN ELETRON), as per the National Information System on Solid Waste Management (SINIR) website from the Ministry of the Environment (SINIR, 2019). All electrical and electronic product manufacturers and importers that manufacture and import products listed in the sectoral agreement are required to structure reverse logistics systems for their products after consumers have used them. These reverse logistics systems must be independent of public urban cleaning systems.

Data on WEEE in Brazil are limited. It is estimated that approximately 2.143 million tons of WEEE were generated in 2019 (Forti et al., 2020). Per capita averages were around 10.2 kg, higher than worldwide averages at 7.3 kg per capita. In Brazil, however, this average will tend to increase as people improve socially. One worrying fact is the lack of accurate data on WEEE collections and recycling in Brazil since there are

Fig. 5. Recycling techniques per module type.
Source: The authors of this study, adapted from Xu et al. (2018)

still no adequate collection systems in many regions. One explanation for this is the lack of specific legal provisions on WEEE.

No data on MSW is included in the WEEE generation data in Brazil because MSW is not included in the list of products in the sector agreements. This may be because Brazil only recently started regulating PV systems via National Electric Energy Agency (ANEEL) Normative Resolution 482 from April 17, 2012 (Brazil, 2012), which may explain the insignificant quantities of reported PV waste products. Likely, most manufacturers, importers, the public, and regulatory authorities lack immediate concern for this issue since the average lifespan of these systems is 25 years.

Presidential decree number 10,240 was published on February 12, 2020, which regulated item VI of the heading of article 33 and article 56 of law 12,305/2010, thereby including Brazil in the list of countries that possess normative provisions or regulations on electronic waste, or domestic waste in this case (BRASIL, 2020). This decree establishes norms for implementing mandatory reverse logistics systems for electrical and electronic domestic use products and their components (BRASIL, 2020). The list of reverse logistics electrical and electronic equipment did, however, include PV panels. So, in a way, Brazil has adopted a strategy

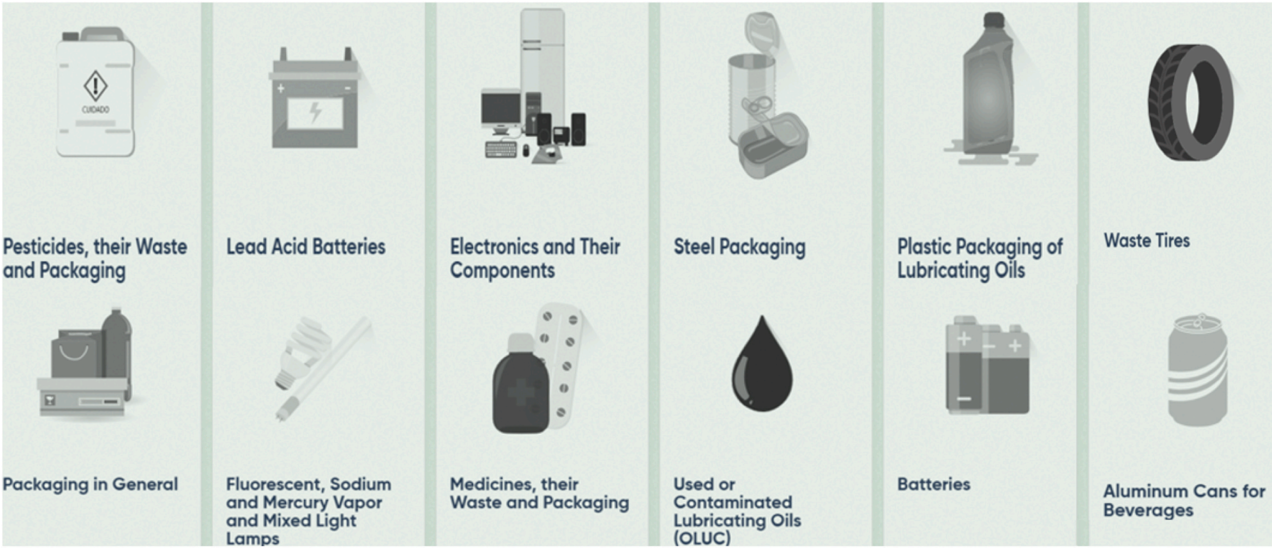

Fig. 6. Reverse logistics systems that have been implemented.
Source: SINIR, adapted by the authors of this study (2021)

similar to that of Europe, via directive 2012/19, by not establishing an exclusive legal structure for the PV issue, but rather by including PV within the legal scope of e-waste generally. Given the legal structure to which Brazil must now adapt, relative to WEEE, aspects like future financing for PVSW reverse logistics must also be established, since Decree No. 10240/20 establishes that funds from companies will be paid using a direct payment system to management agencies, or using individual systems. It is likely, however, that mechanisms similar to some European countries will be adopted in the near future in Brazil, because clear responsibilities for all players will need to be defined and encompass all PVSW generated before and after any regulatory frameworks.

Once the regulatory issue has been resolved via a well-defined financing mechanism, which will be integral in allowing Brazil to manage its PVSW issue, Brazil will have to prepare its infrastructure to properly handle all PVSW, and fundamentally develop industries that are technologically prepared to efficiently process all end-of-life phases of PVSW processing. This is undoubtedly a most difficult task, since industries that recycle noble and rare elements from electronic waste are practically inexistent in Brazil. Companies that do perform this type of work only recover lower added value elements, like lesser noble metals, plastics, glass, etc. Another point worth mentioning is the issue of PV module recycling technology patents if Brazil does not develop its own technologies, and Brazil will have to address this in the future.

Given the many challenges associated with properly managing end-of-life PVSW, several studies unanimously agree on one point, i.e., PV panel recycling can provide environmental and economic sustainability by creating new business opportunities (Fiandra et al., 2019; Latunussa et al., 2016; Mahmoudi et al., 2021). This is corroborated by the fact that the financial, environmental, and energy costs required to process recycled silicon are much lower than raw material extraction costs (D`Adamo et al., 2017). Current and future PV modules can be recycled, and this constitutes an opportunity for researchers and companies who may seek to produce new products from recovered recycled elements, and should, therefore, be a highly sought-after future goal.

7. Conclusion

Human needs for transforming and using energy have always led to some environmental impacts. Regarding Photo Voltaic System Waste (PVSW), PV equipment production requires materials and energy, and PVSW waste is produced at the end of operational life cycles. However, the biggest problem is not the volume of produced waste, but rather the volume of improperly treated waste, similar to other WEEE, and this is exacerbated as society improves economically. It is expected that total generated PVSW will vary from 60 to 78 million tons worldwide by 2050.

Studies from the Global Waste Monitor, 2020, indicate that about 2.143 million tons of WEEE were produced in Brazil in 2019, i.e., a per capita average of 10.2 kg, which is higher than the world average (7.3 kg). Furthermore, there is a strong upward trend Forti el al., 2020. However, these numbers make no reference to PVSW, confirming the need for concern regarding the PVSW waste volumes that will be produced in Brazil in the future. The fact that Brazil has not yet expressed concern, nor provided concrete actions for dealing with generated waste volumes when current systems reach the end of their useful lifespans, is perhaps best understood given that Brazil only recently started implementing PV power on a wide scale.

Based on estimated PV lifespans, forecasts point to considerable PVSW volumes at the end of a 30-year period, further increasing the total per capita volume of generated WEEE in Brazil. Therefore, potential impacts and challenges associated with PV solar energy in Brazil merit careful evaluation, given its growth. Although the benefits of using PV energy are clear, uncontrolled end-of-life system disposals can lead to serious environmental damage and tarnish any image of sustainable electricity production, especially given the dangerous and rare chemicals that PV systems contain, like lead, cadmium, tin, silver, silicon, etc., which, if improperly disposed of, will be difficult to recover, or lost forever, thereby causing environmental damage and harm to living beings alike.

More efficient technological solutions and processes will need to be developed to adequately handle problems related to end-of-life PV systems. However, this alone will be insufficient since political mechanisms and structures will also need to be developed and implemented. Appropriate regulatory requirements will be needed at all stages of the PV system life cycle to prepare and encourage industrial development for adequately treating PVSW. The lack of industries that produce PV systems in Brazil is also a major obstacle to developing a recovery and recycling chain for valuable materials contained in PVSW. Brazilian researchers and Brazilian industries also face other technological challenges since Brazil does not possess efficient technologies for recycling PV systems, making Brazil technologically dependent on other nations. Congruently, this also presents an opportunity, as public authorities, academia, and industries have a chance to develop the needed infrastructure, concepts, and values for a circular economy, thereby contributing to the sustainable development of the PV industry in Brazil.

Finally, sector agreements on Electrical and Electronic Equipment addressing the WEEE problem indirectly encompass the PVSW problem. Sector agreements list equipment and devices for which responsible entities must have reverse logistic systems in place. However, PV systems are not yet included in the sector agreements. This could constitute an opportunity for industries to adapt by including PVSW in its sector agreements on electrical and electronic equipment or by creating a specific Sector Agreement to address PV generation equipment.

The implementation of mechanisms that will enable the execution of actions that promote the reduction, reuse, recycling of RSFV products. It will be essential to create partnerships between public authorities and society so that all actions are well implemented. Parallel to the Brazilian normative evolution, measures and good practices, already applied in other countries, must then be adapted to the reality of Brazil. Therefore, future discussions and proposals will be necessary for the implementation or adequacy of models and standards applied in other regions for the Brazilian reality.

A final analysis is in order. If PV systems were to be included in sector agreements, or if legal instruments are established, any systems installed before said agreement or law was to go into effect must also be included, so these systems are not exempt from responsibly and appropriately treating their end-of-life waste. It is quite clear, however, that the longer it takes to define solutions to this issue, the greater the future liabilities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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