ABES

Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Separating materials from photovoltaic panels through thermomechanical processes and laser beams for the extraction of metals

Separação de materiais de painéis fotovoltaicos por meio de processos físicos

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ABSTRACT

Usually, a photovoltaic panel is composed of either monocrystalline or polycrystalline silicon cells that convert sunlight into electricity, with an average lifespan of nearly 30 years based on a guaranteed performance outlet of 80% power. After this period, the panels turn into waste and must be discarded properly, with recycling materials being the most resourceful method. The initial goal of this research was to develop a physical pre-treatment method aiming at separating components and determining adequate speed and power necessary for the removal of the sealant (ethylene vinyl acetate [EVA]) present in photovoltaic cells. This would enable easier extraction of commercially valuable metals, such as silver, metallic silicon, copper, and aluminum utilizing a laser beam. The methodology involved utilized photovoltaic cell samples subjected to a thermomechanical pre-treatment to remove prior components, followed by the application of a laser beam at varying potency and velocities to find the optimal settings to remove EVA present in samples without a backsheet foil. After removing the EVA, manual extraction of copper ribbons, silver filaments, and metallic silicon was carried out using a micro-grinder and a mill, producing a powder that was then analyzed by X-ray fluorescence (XRF). The results showed that the initial components (junction box and backsheet foil) could be removed through thermomechanical processes , followed by EVA removal using a 400 W laser beam at 200 mm/s. Following that, the copper ribbons, with an average content of 91.71% Cu, were separated manually. Silver and metallic silicon recovery through milling resulted in a powder with 0.6% Ag and 93% Si content.

Keywords: photovoltaic panel; recycling; laser beam; silver; silicon; circular economy.

RESUMO

O painel fotovoltaico é composto de células de silício que convertem a luz solar em energia elétrica, apresentando vida útil média de 30 anos. Após esse período, os painéis precisam de um destino ambientalmente aceitável. O objetivo inicial deste trabalho foi desenvolver um pré-tratamento físico para separar componentes e encontrar a potência e a velocidade adequadas para a remoção do selante presente nas células fotovoltaicas com o uso de raio *laser*, visando facilitar a separação de metais de interesse comercial como prata, silício metálico, cobre e alumínio. A metodologia foi baseada no uso de células fotovoltaicas submetidas a um pré-tratamento termomecânico para a remoção de componentes e, depois, o uso de raio *laser* com diferentes potências e velocidades para encontrar a combinação adequada de parâmetros para a remoção do selante presente nas células fotovoltaicas. Após a remoção do *ethylene vinyl acetate* (EVA), foi possível a retirada manual das fitas de cobre, bem como a remoção dos filamentos de prata e do silício metálico com uso de uma microrretífica e uma fresadora, obtendo-se um pó que foi analisado por fluorescência de raios X. Os resultados mostraram que é viável remover a *junction box* e o *backsheet foil* por um processo termomecânico e, em seguida, remover o EVA com raio *laser* com a potência de 450 W a 200 mm/s. As fitas de cobre, com teor médio de 91,71% de Cu, foram separadas manualmente. A remoção da prata e do silício metálico com a fresadora gerou um pó com 0,6% de Ag e 93% de Si.

Palavras-chave: painel fotovoltaico; reciclagem; processos físicos; prata, silício, economia circular

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Conflicts of interest: the authors declare no conflicts of interest.

Funding: none.

Received on: 10/28/2024. Accepted on: 07/30/2025

https://doi.org/10.5327/Z2176-94782331

Introduction

Among the goals defined by the United Nations Agenda 2030 (UN, 2023), Goal 7 is highlighted: *Guarantee access to affordable, reliable, sustainable, and modern energy to all*, encouraging the use of photovoltaic solar energy. Goal 12 is also relevant: *Guarantee sustainable production and consumption patterns*, encouraging the reuse and recycling of materials found in photovoltaic panels.

With a global installed capacity approaching 1,865 GW in 2024 (IRENA, 2025), solar photovoltaic energy is making a significant contribution to the supply of renewable electricity worldwide. Therefore, countless solar panels are discarded every day because they have reached the end of their useful life or because they have defects caused by human factors during transportation or installation (Sinha and Wade, 2015), as well as by extreme weather events such as the flood that hit the state of Rio Grande do Sul, Brazil, in 2024, i.e., they are unserviceable modules that cannot be recovered and are discarded irregularly or sent for recycling.

Damaged panels or panels at the end of their lifespan still contain valuable materials with recycling potential. By 2030, the accumulated value of raw materials salvageable in obsolete photovoltaic panels may reach about US$450 million (IRENA, 2016). Recycling these materials not only saves landfills' space but is also environmentally responsible and congruent with Goal 11 of the UN's Agenda 2030 — *Sustainable Cities and Communities*.

Despite the wide variety of equipment available on the market, photovoltaic panels are generally composed of an aluminum frame, a layer of highly transparent tempered glass, a layer of sealant (ethylene vinyl acetate [EVA]), crystalline silicon photovoltaic cells bearing metallic electrical contacts, a second EVA layer, a polymeric backsheet foil, and a junction box that connects to electrical installations (Sica et al., 2018; Ardente et al., 2019; Xu et al., 2019; Rathore and Panwar, 2022). All of these materials can be reused and recycled.

Crystalline silicon (c-Si) technology represents more than 97.5% of the global photovoltaic cell production, mostly fabricated with wafers that use a single silicon crystal (Barbose and Darghouth, 2019) with a purity of 99.9999%. These wafers are doped with boron, phosphorus, and aluminum (Sadhukhan et al., 2021), offering efficiencies between 20 and 25% and an estimated lifespan of 30 years (IEA, 2023).

However, a significant number of photovoltaic panels turn unserviceable long before their estimated lifespan due to damage during installation, climatic events, component failures, or replacement with newer, more efficient modules (Tao et al., 2020; Tan et al., 2022). This is expected to result in an estimated 8 million tons of photovoltaic waste by 2030 (Heath et al., 2020), demanding recycling of materials necessary for the production of new equipment.

Generally, photovoltaic cells are interlinked by front-end silver contacts and rear-end aluminum-silver alloy contacts, creating electrical contacts (Klugmann-Radziemska et al., 2010), while copper ribbons are soldered to the cells with a lead-tin alloy (Pagnanelli et al., 2017).

In Brazil, the recycling of photovoltaic panels is legally required according to the National Policy of Solid Residues (PNRS) (Brazil, 2010; 2020), which establishes the necessary framework for the administration and management of solid residue within the national territory, congruent with upheld legislation in the European Union (European Union, 2012).

The PNRS defines guidelines for the integrated management and environmentally sound handling of solid waste, including electronic equipment such as photovoltaic panels. It establishes principles, objectives, and instruments that promote shared responsibility and reverse logistics for this type of product, promoting waste reduction, environmental protection, and a circular economy. This approach aims to reintegrate recycled materials, including photovoltaic panels whose components can be reused in new products, into the production chain (Brazil, 2020).

Thus, there is a need for innovative solutions to recycle electronic waste, particularly photovoltaic panels, as demand is expected to increase significantly within the next few years. Brazil currently possesses 2.1 million systems containing photovoltaic panels, racking up 23.5 GW distributed across the national territory (Brazil, 2023).

Recycling processes for photovoltaic panels with the purpose of extracting commercially valuable metals such as silver, copper, and aluminum can be classified as chemical, thermal, or mechanical, with combinations necessary depending on the type of panel to be recycled and the scale of operation, whether local or industrial, with varying levels of mechanization.

In this sense, the thermomechanical recycling process shown in this article may offer a solution to a serious environmental and economic challenge. Despite all legal requirements, only 2% of electronic waste in Brazil is recycled, due to collection costs and operational difficulties in transporting those items to appropriate locations (Brazil, 2019). In other words, adequate infrastructure does not exist for the processing of obsolete photovoltaic panels (Markert et al., 2020).

The very first step in the proposed thermomechanical recycling process entails removing the aluminum frame, backsheet foil, wiring, and electrical connections, as well as separating the photovoltaic cells from the tempered glass through heating and scraping. This is followed by sealant removal with the use of laser beams, after which the photovoltaic cells are sent to specialized companies for chemical recycling of commercially valuable metals.

The thermomechanical process is crucial for the circular economy[1] (Papamichael and Zorpas, 2022; Van Opstal and Smeets, 2023), as the

[1] Circular economy is an economic model that aims to maximize the efficient use of resources by promoting the reuse, recycling, recovery, and regeneration of materials and products throughout their life cycle. This seeks to maintain the value of products and materials for as long as possible, in line with the United Nations (UN) guidelines through programs such as the United Nations Environment Programme (UNEP, 2024), highlighting the circular economy as part of the Sustainable Development Goals (SDGs) (UN, 2023).

aluminum frame, wiring, and tempered glass can be recycled and reused locally, generating employment and wages, while the photovoltaic cell materials, of higher value, require complex processing at specialized facilities.

The sealant (EVA) protects photovoltaic cells from moisture and atmospheric oxygen (Fouad et al., 2017), offering optical and electrical transmissivity and ensuring performance and reliability at low costs for decades. However, it becomes an obstacle to the proper recycling of photovoltaic panels, as shown in Figure 1.

To remove the sealant encasing photovoltaic cells, chemical processes utilizing solvents such as toluene (CAS 108-88-3) are employed. Toluene is a highly combustible and carcinogenic substance that requires heating and stirring for long periods (Brenes et al., 2023), or pyrolysis at very high temperatures for multiple hours, causing environmental damage (Fiandra et al., 2019). In addition to organic solvents for dissolving the EVA sealant present in photovoltaic cells (Doi et al., 2001), the chemical process utilizes acidic and alkaline solutions to concentrate commercially valuable metals, which requires milling of the panels.

The thermal process is efficient at removing EVA and allows for recycling of up to 90% of the components in a photovoltaic module (Nieland et al., 2018), but it demands high energy consumption and causes environmental impacts (Tao and Yu, 2015; Xu et al., 2018), as the thermal degradation of fluorine compounds present in backsheet foils can generate dioxins (Aryan et al., 2018).

This research looks for an innovative alternative through the use of laser beams to thermally degrade EVA, offering a swift and economic process. EVA removal from the surface of photovoltaic cells facilitates the chemical attack for leaching commercially valuable metals, allowing for silver extraction from photovoltaic panels without necessitating component milling.

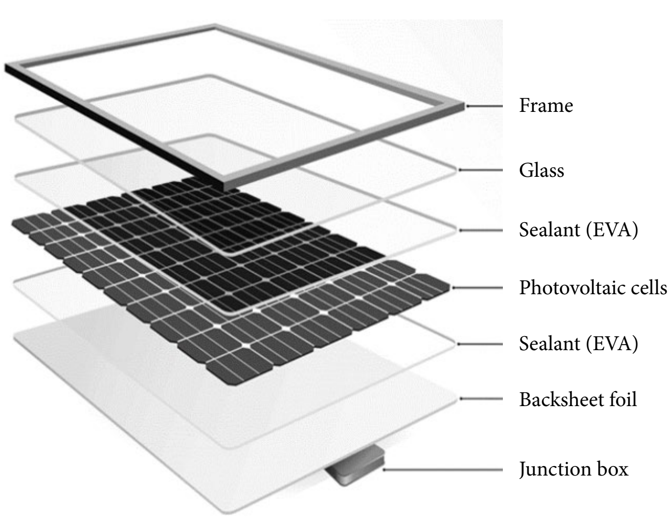

Figure 1 – Photovoltaic panel.
Source: Clean Energy Reviews (2022).

The presence of silver justifies this recycling process, as photovoltaic panels contain, on average, 20 g of silver (APMEX, 2022).

After the extraction of commercially valuable metals from a photovoltaic cell, silicon pads with a thickness of 200 μm may remain, which can be utilized as metallurgical-grade silicon, with purity of up to 99%, priced at around US$4 per kilogram. Alternatively, after further processing, it may be used as silicon of solar degree with a minimum purity of 99.9999%, which costs, on average, eight times more than the metallurgical-grade silicon (Peplow, 2022).

Recycling also reduces the environmental impact of producing new photovoltaic panels (D'Adamo et al., 2023) by incentivizing the optimization of current methods through deepening of research for new technologies. Photovoltaic panel recycling also prevents improper disposal, mitigating risks to human health and the environment caused by toxic metals such as lead, chromium, and nickel, which can contaminate soil. It also addresses hazards from bromate and fluorinated polymer flame retardants present in the backsheet foil (Padoan et al., 2019), whose combustion can release toxic compounds such as fluorocarbons, dioxins, furans, and benzene (Danz et al., 2019).

This research work aims to present the following main goals: the first objective was to find the optimal speed and power for laser beam removal of the sealant (EVA) present in photovoltaic cells, compared to chemical and thermal processes, while the second goal was to extract silver filaments and metallic silicon utilizing a computer numerical control (CNC) mill, resulting in a silver and silicon powder.

Materials and Methods

In this work, five polycrystalline silicon photovoltaic panels were used, with a maximum power rating (*W*p) of 10 W, dimensions of 240 × 350 × 17 mm, and an approximate weight of 836 g. Manufactured in 2023, the panels had an energy efficiency of 11.9% (low efficiency), according to the National Institute of Metrology, Standardization and Industrial Quality (INMETRO, 2017).

The methodology was carried out in three steps: (i) a thermomechanical process to separate the initial components of the photovoltaic panel; (ii) removal of the sealant (EVA) layer that encases photovoltaic cells through the use of a laser beam; and (iii) mechanical extraction of copper filaments and metallic silicon through a micro-grinder and CNC mill, as depicted in Figure 2.

Thermomechanical process for component separation

The aluminum frame was removed mechanically, while the junction box and backsheet foil were manually removed with the help of a 2 kW heat gun at 300°C and a metallic spatula after heating. The thermomechanical removal of the backsheet foil avoided the combustion of its polymeric components, which are potential pollutants, and may have reduced the time needed for laser usage to remove sealant (EVA).

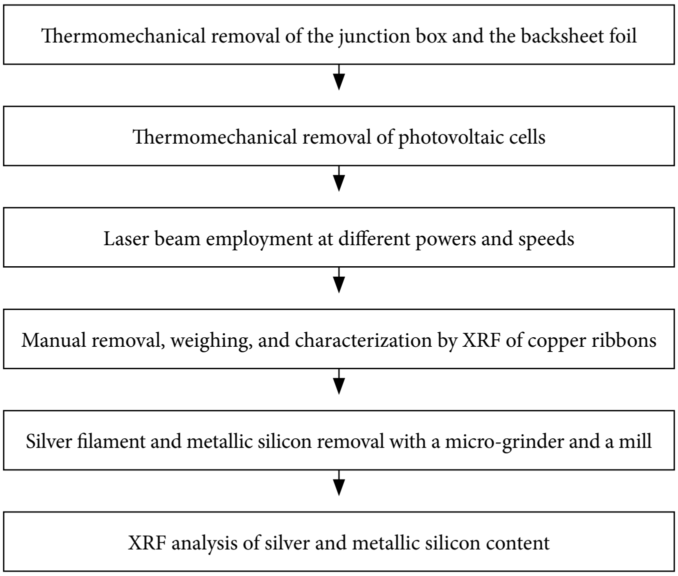

Figure 2 – Simplified flowchart of the thermomechanical process.

Photovoltaic cells were removed with a metallic spatula after heating the sealant with the heat gun.

EVA removal from cells with a laser beam

Following the thermomechanical process to separate components, 30 samples, each composed of one photovoltaic cell, were subjected to a laser beam at varying speeds and power levels, with the samples mounted on medium-density fiberboard (MDF) supports. Power levels tested varied from 300 to 525 W, and speed levels from 100 to 300 mm/s, looking to discern the best results for removing the sealant (EVA).

The laser tests lasted less than 1 min for each sample, while the thermal degradation of the EVA film in an electric furnace, used in some processes, lasted an average of 3 h at 500°C. Similarly, chemical removal using solvents also requires heating for long periods of time.

Sealant (EVA) removal from the photovoltaic cells using the laser beam enabled the manual extraction of copper ribbons for future salvaging of commercially valuable metals, but the cells remained fixated to the tempered glass, facilitating chemical treatment for silver recovery.

After initial testing with the laser beam, the samples were examined under an optical microscope to detect EVA residues on the surface of the photovoltaic cells to confirm the optimal power and speed parameters.

Upon defining the best parameters, a new panel, with its aluminum frame and backsheet foil previously removed, was treated with the laser beam to remove the photovoltaic panel sealant, followed by retrieval of the copper ribbons using manual tools.

Silver filament and metallic silicon extraction

After extracting the copper ribbons, a micro-grinder with a cone-shaped diamond tip was manually employed to remove the silver filaments and metallic silicon from the photovoltaic cells. This process was carried out without removing the EVA from the lower layer and without damaging the tempered glass. The resulting material was a powder, which was then sifted and analyzed by X-ray fluorescence (XRF).

In a second stage, aiming at optimizing the process, improving operational safety, reducing costs, and minimizing sample contamination, the silver filaments and metallic silicon were removed with the use of a CNC mill. This was carried out in two steps of 1.5 mm, at a speed of 50 mm/min, also resulting in a powder that was subsequently sifted and analyzed by XRF.

Results

Thermomechanical process for component separation

The thermomechanical separation of photovoltaic cells proved to be practical and economical, requiring simple tools and allowing cost reductions for separating commercially valuable metals such as silver, copper, and aluminum. Figure 3 shows the sequential steps involved in removing the initial components.

EVA removal from cells with a laser beam

During laser beam employment, charring of the MDF supports, used for attaching the samples, and the metallic silicon fragmentation indicated that excessive power was applied for removing the sealant (EVA) from the photovoltaic cells, but manual recovery of the copper ribbons was still possible. The charring suggests that excessive power was used for the laser beam, as the temperature required for MDF incineration exceeded over 750ºC (Brazil, 2017).

The main results of using the laser beam are shown in Table 1 and Figure 4.

After defining initial parameters for laser beam power and speed, aiming at total extraction of the sealant (EVA), the process was applied to a whole photovoltaic panel, with the aluminum frame and backsheet foil removed, utilizing 450 W of power and a speed of 200 mm/s. The procedure took 46 min and 11 s, with a power consumption of 1.24 MJ. However, by the end of the experiment, it was noted that the tempered glass had been shattered from localized expansion due to heat concentration originating from the laser.

Silver filament and metallic silicon removal

Figure 5 shows the powder obtained from milling.

XRF analysis showed that large copper ribbons, such as those in Figure 4C, contained on average 34.824% copper (Cu), 36.566% lead (Pb), and 23.374% tin (Sn), while the narrow copper ribbons, also shown in the same figure, showed average contents of 47.476% copper (Cu), 30.578% (Pb), and 19.103% tin (Sn).

Figure 3 – Different stages of the dissassembly of a solar panel. (a) Photovoltaic panel's back; (b) Photovoltaic panel's back without a junction box; (c) Photovoltaic panel's back without tags and frame; (d) Junction box contact detailing; (e) Panel's backside with the backsheet foil being removed; (f) Photovoltaic cells exposed before recovery with the assistance of a metal spatula and a heat gun.

Table 1 – Relation between laser beam's power [w] and speed [mm/s].

Power and speed	Effect
525 W and 300 mm/s	MDF support charring
525 W and 250 mm/s	MDF support charring
525 W and 200 mm/s	MDF support charring
525 W and 150 mm/s	MDF support charring with photovoltaic cell fragmentation
525 W and 100 mm/s	MDF support charring with photovoltaic cell fragmentation
450 W and 200 mm/s	MDF support charring without photovoltaic cell fragmentation
300 W and 300 mm/s	Presence of EVA residues
300 W and 250 mm/s	Presence of EVA residues
300 W and 200 mm/s	EVA removal without photovoltaic cell fragmentation
300 W and 150 mm/s	EVA removal with photovoltaic cell fragmentation
300 W and 100 mm/s	EVA removal with photovoltaic cell fragmentation

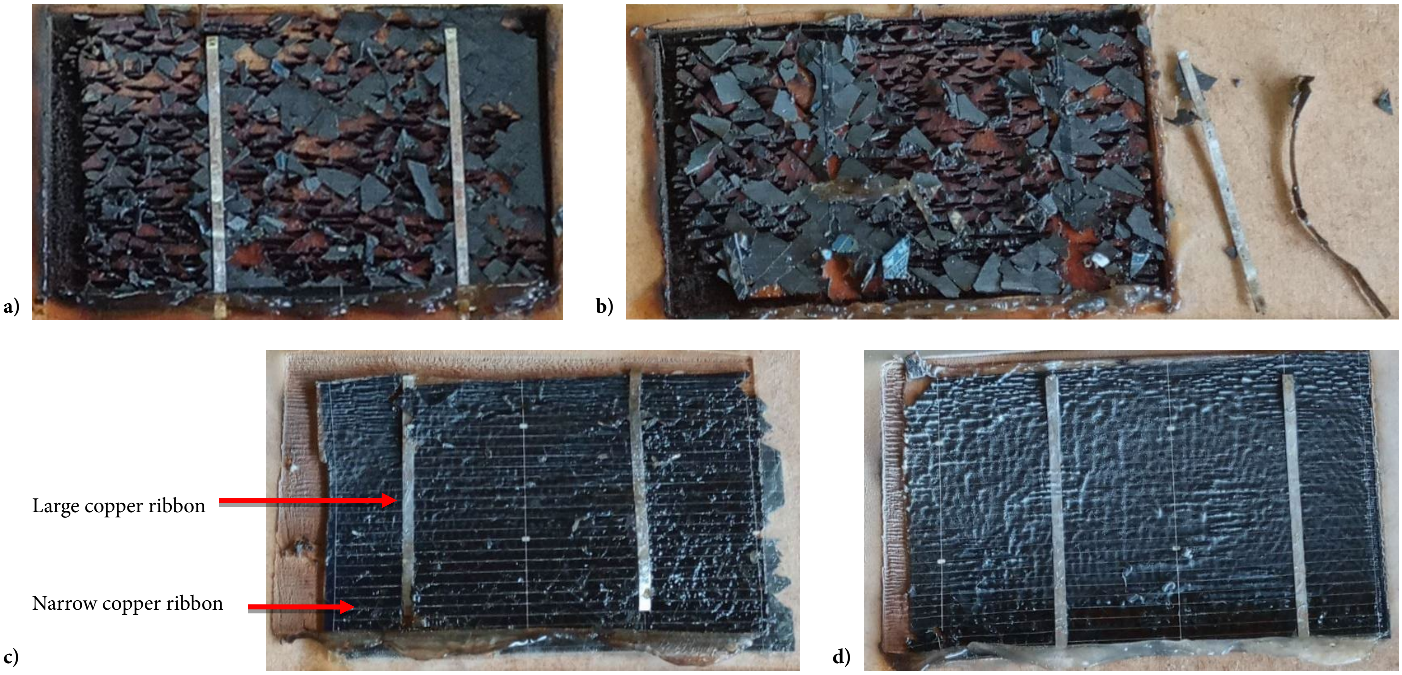

Figure 4 – The solar panel after being charred by the laser beam, and the exposed copper ribbons after residue removal. (a) Support charring with photovoltaic cell fragmentation; (b) Manual removal of copper ribbons; (c) EVA removal without photovoltaic cell fragmentation; (d) Presence of EVA residue on the sample.

Figure 5 – Sifted silver and metallic silicon powder.

After removal through sanding off lead and tin lining, used to increase the resistance and durability of copper against corrosion (Coppermetal, 2024), XRF analysis showed that the large copper ribbons contained 94.971% copper (Cu), 2.778% lead (Pb), and 1.610% tin (Sn), while the narrow copper ribbons contained 88.452% copper (Cu), 7.583% lead (Pb), and 3.865% tin (Sn). The lead and tin contents indicated are most likely due to the presence of these elements at the opposite side of the sample, where the lining had not been removed.

XRF analysis showed that the powder retrieved from photovoltaic cells using a micro-grinder showed an average concentration of 0.73%±0.01% silver (Ag) and 95.04%±0.47% silicon (Si), congruent with results reported in the literature (Dias et al., 2016). The powder also contained an average of 0.85%±0.01% copper (Cu) and 2.41%±0.17% aluminum (Al).

XRF analysis showed that the powder retrieved from photovoltaic cells using a mill showed an average concentration of 0.60%±0.01% silver (Ag) and 92.73%±0.56% silicon (Si), as well as an average of 3.82%±0.06% copper (Cu) and 2.01%±0.18% aluminum (Al).

This result diverged most likely due to the higher copper content found in the copper ribbons located at the base of the photovoltaic cells, as shown in Figure 6.

Conclusions

The results obtained are important to broaden the knowledge on the recycling of photovoltaic panels and support the implementation of the presented process on a large scale, reducing both costs and environmental impacts associated with the recovery of metals with commercial interest, especially silver.

The method proposed in this research, consisting of a thermo-mechanical pre-treatment that involves removing the backsheet foil using a heat gun and a spatula to prevent combustion of potentially

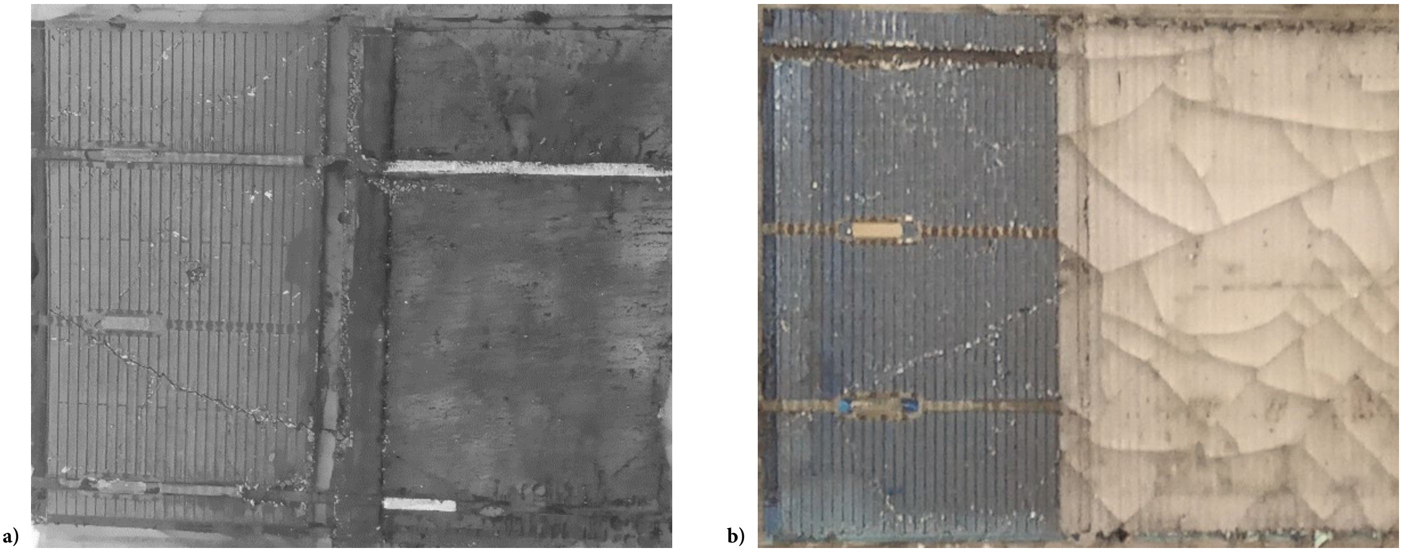

Figure 6 – The photovoltaic cells after the removal of silver and metallic silicon using physical processes. (a) Photovoltaic cells removed using a micro-grinder. (b) Photovoltaic cells removed using a mill.

toxic components, combined with sealant (EVA) removal using a laser beam, proved to be simpler than the chemical and thermal processes.

The thermomechanical stage allows for the removal of the junction box, wiring, and backsheet foil using simple tools, according to the precepts of the circular economy. It is the most adequate alternative from an economic and environmental standpoint, when compared to chemical processes that require the use of solvents such as toluene or thermal processes like pyrolysis, which require high temperatures in an oven with an inert atmosphere.

In this context, the removal of the sealant (EVA) using a laser beam also has advantages over chemical and thermal processes. It is easily scalable for industrial use, allowing the quick separation of metals of commercial interest at a lower cost and with reduced environmental impact. The quantification of energy consumed in the process, 1.4 MJ, allows for the comparison of energy consumption with other processes.

Manual removal of copper ribbons from photovoltaic cells can be replaced with greater efficiency, speed, and safety by milling, allowing for the separation of concentrated copper material with an average content of 91.711%. The mill also allows for the removal of silver and metallic silicon with efficiency and low energy consumption, without the need for potentially dangerous and environmentally harmful chemicals. The dust obtained in this step contains 0.6% Ag and 93% Si, which is a highly concentrated fraction of these two metals of interest.

This research contributes to the development of new processes for recycling photovoltaic panels that are closer to the circular economy concept, especially in Brazil, where more than 800,000 waste pickers (IPEA, 2022) often work in dumps, which remain the main destination for solid waste in the country, and are present in more than 30% of Brazilian municipalities (IBGE, 2023).

Authors' Contributions

Pavani, S.: writing––original draft; **Pavani**, G.: writing––review and editing; **Veit**, H.: supervision.

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