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SWOT Analysis of Different Photovoltaic Panel Recycling Processes for the Brazilian Reality

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Abstract: Despite being considered a form of green energy, Photovoltaic panels face a logistical challenge when it comes to proper disposal. As the end-of-life for first-generation panels approaches, exploring methodologies more suitable for the Brazilian context is essential, as this technology has not yet been widely adopted. This study analyzed recycling treatment methods from photovoltaic modules using the SWOT analysis tool, focusing on the Brazilian economy scenario. It used bibliometric searching for methodology. The three main comminution methods—thermal, physical, and chemical—were discussed among the other methods available for photovoltaic panel recycling. Scenario identification was used to evaluate these methods by cross-referencing the factors of the SWOT matrix to determine how each technique fits into a growth, development, maintenance, and survival scenario. The study concluded that the most suitable treatment method for Brazil's reality is thermal treatment, explicitly utilizing the Solvothermal Expansion with Thermal Decomposition (SSTD) or Electrothermal method, chosen from 11 possible methods. It was found that all chemical and physical treatments can produce some form of toxic effluent/waste during the process. In contrast, thermal treatments are already widely commercialized and make the smallest number of toxic compounds, dependent only on the energy source.

Keywords: photovoltaic panel; delamination; SWOT analysis; recycling

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1. Introduction

Oil, which is currently considered the world's primary source of energy, has been criticized for the damage it has been causing to the environment. The main problems are characterized by global warming, the release of polluting gases into the atmosphere, and the contamination of water bodies and soil [1–3].

Concerning sustainability, fossil fuels are seen as the great villains of today, and the generation of gases can vary between 400 and 1000g.kWh-1 of CO2 emissions in thermal plants with no effective way of mitigating them [4]. This is because the energy conversions between fuel and effluent are disproportionate to current environmental standards. In addition, fossil fuels are considered a limited energy source. Thus, searching for new, carbon-free energy sources is challenging [1–3,5,6].

On the other hand, photovoltaic energy is considered one of the energies of the future. It is an emerging energy source worldwide, generating a considerable amount of energy in a more accessible way to the general public without generating greenhouse gas (GHG) emissions. Since 1999, this energy type has grown substantially due to German, Spanish, and Japanese programs integrating photovoltaic modules into buildings and urban areas [7]. Although these modules cause some environmental impact during the initial manufacturing stage, they allow residential installations to produce the energy they consume without generating pollutants during energy production [2,4]. Even though they promote energy generation more sustainably, photovoltaic panels present a major logistical challenge regarding their correct disposal after the end of their useful life [1,5].

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A photovoltaic panel is mainly made up of a photovoltaic cell, which has, on average, an estimated useful life of 25-30 years. Even with the technological advances and advantages of photovoltaic energy, it is already possible to feel the effects of its mass disposal due to few actions for the correct disposal of this type of material [1,5,7]. A photovoltaic panel comprises toxic materials such as cadmium, indium, gallium, and silicon, further aggravating the situation if disposed of improperly. The race for panels produced by companies and non-governmental organizations (NGOs) that allow for a module with a longer lifespan and biodegradability has been challenging. However, they still require disposal and adequate treatment of the components that make up the solar panel [5].

Photovoltaic energy can be considered an "energy of the future" due to the extensive possibilities for recycling and reusing the materials used to construct new and existing photovoltaic panels [2,8]. This research sought to evaluate the recycling methods commonly known in the industry to define which would be most advantageous for the Brazilian reality.

2. Materials and Methods

SWOT analysis is a tool that allows examining and identifying the advantages and disadvantages of a specific process based on four main patterns. These patterns are defined as strengths, weaknesses, opportunities, and threats, and their matrix can be identified in Table 1. These are evaluated by internal or external factors and positive or negative factors [9].

Table 1. SWOT matrix with the main factors.

Factors	Internal	External
Positives	Strengths	Opportunities
Negatives	Weaknesses	Threats

Since many of the recycling methods studied have factors in common, a compilation of general factors was previously carried out. These were obtained from a bibliographic study related to the topic of photovoltaic panels or only WEEE recycling. Thus, after compiling these factors, it was identified which method would correspond to which factors to better characterize these.

In addition, a cross-referencing of their factors was carried out for each type of treatment. In this way, it was possible to identify strategic responses for each addressed method [9,10]. The combination of factors results in: S-O (Growth), W-O (Development), S-T (Maintenance), and W-T (Survival), where:

- Growth - The strategy is favorable, and the current strengths can stand out. A favorable situation for investments;
- Development - The main objective is to take advantage of current opportunities and transform weaknesses into something positive through them;
- Maintenance - The situation is to not fluctuate in its main patterns, using internal strengths to mitigate threats;
- Survival - The worst possible scenario, requiring difficult choices that require complete change or abandonment of the process;

This combination of factors was performed based on the sum of the number of factors each method has. Therefore, the process with many strength and opportunity factors will be favorable in a growth scenario (S + O). This type of matrix is identified as the TOWS matrix.

Considering that the methods already been studied have positive and negative points in their process, these were used as parameters of the strengths and weaknesses of the matrix. Therefore, the opportunities and threats require a broader scope and, consequently, were based on bibliographies and laws encompassing sustainability and SWOT analysis in general [10,11]. They do not directly reference the recycling of photovoltaic panels but present valid indicators for addressing the SWOT of treatment methods and environments in WEEE recycling [9–11].

3. Results

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The results were divided between the recycling methods studied and the SWOT matrices produced.

3.1. Recycling Methods

To evaluate the recycling methods, we sought to address all existing methods of relatively new technology. This explanation is due to the lack of information on the subject and the fact that many methods are still being developed. Therefore, the data were obtained from bibliographical references. Furthermore, some methods differed due to slight variations in temperature, time, or solution concentration. These were grouped into a single method since they would not make a difference in their main factors for the SWOT analysis. Table 2 represents the physical, chemical, and thermal methods, respectively.

Table 2. Compiled methods of recycling most commonly known photovoltaic modules.

Treatment	Method	Working Principle	Panel Generation	Ref.
Physical	Hot Knife	• Separating the glass from the EVA/cell layer with a heated cutter	1ª	[12–14]
	High Voltage Pulse	• Microexplosions in the aluminum electrode and silicon substrate, which separate the glass and backsheet layers	1ª	[12–15]
	Crushing/Grinding	• Staged crushing on a mobile device with hammer or knife mills	1ª e 2ª	[12,14,16]
	Laser	• The aluminum and silver electrodes present in the EVA absorb the pulsed laser energy. Increase in the temperature of the EVA/cell. Weakening of the adhesive force on the back of the EVA	1ª	[14,17]
Thermal	Combustion/Pyrolysis	• Burning the panel in a kiln	1ª	[13,14]
	Electrothermal	• 400W RF heating		
	Solvothermal Swelling with Thermal Decomposition (SSTD)	• Solvothermal reactor has been pretreated with organic solvent. Heating occurs to form vapor from the organic solvent. Reactor for decomposition/combustion of EVA.	1ª	[12]
Chemical	Organic Solvent	• Immersion in organic solution for a long period	1ª	[5,12,14]
	Inorganic Solvent	• Immersion in an inorganic solution with ethanol for a long period	1ª e 2ª	[12]

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Organic Solvent with Ultrasound	• Dissolution of EVA at 70°C in 3M toluene; however, the photovoltaic cell showed several cracks. 450W	1ª	[5,17]
Supercritical CO_2	• Immersion in organic solution in the presence of supercritical CO_2	1ª	[12]

3.2. SWOT Analysis

To perform the SWOT analysis, it was necessary to prepare a list of technical and environmental aspects of each process to identify which would be most advantageous in a circular economy.

The list of strengths, weaknesses, opportunities, and threats is compiled in Tables 3, 4, and 5, considering the possible positive and negative aspects and internal and external factors. Thus, each method will only focus on these factors in its SWOT analysis in Table 6.

A simple system was developed as an acronym for each factor to differentiate them. In this, the first character represents the means of treatment, the second represents the SWOT factor, and the third is just a number.

Table 3. SWOT factors compiled from possible physical methods.

Treatment	Strengths	Weaknesses	Opportunities	Threats
Physical	PS1 - Simple treatment of generated waste [5]	PW1 - Considerable noise generation [17]	PO1 - Most processes work with 1st and 2nd generation modules	PT1 - Low commercialization compared to chemical and thermal [5]
	PS2 - Possible separation into several residues [5]	PW2 - Poor separation quality, mixing toxic metals with other components [17]	PO2 - More economically viable [11]	PT2 - There is no means of recovering the cell for reuse [17]
	PS3 - There is no emission of toxic effluents into the environment [17]	PW3 - High equipment wear and tear	PO3 - No inputs are required, only equipment [11]	PT3 - Need for additional treatment for separation of components with higher purity [17]
	PS4 - Easy EVA removal [17,18]	PW4 - Expensive equipment	PO4 - Smaller scale, easy applicability [11]	PT4 - High maintenance due to equipment wear and tear [11]
	PS5 - Glass recovery [17,18]	PW5 - Most methods are on a laboratory scale		PT5 - Legal Framework for Solid Waste National Policy (PNRS), Brazilian Law n°12.305/2010 [20]
	PS6 - Can be used with any size or shape of module [17]	PW6 - Production of toxic dust [5]		PT6 - Bench scale [11]
	PS7 - Economically viable [18]	PW7 - Possible breakage of the photovoltaic cell [14]		

		PW8 - It does not work if the module is previously physically damaged. [17] PW9 - Slow process [17] PW10 - Process control required [19] PW11 - Only works on rear EVA [19]		

Table 4. Compiled SWOT factors of possible thermal methods.

Treatment	Strengths	Weaknesses	Opportunities	Threats
Thermal	TS1 - Total elimination of EVA [5]	TW1 - High energy expenditure [5]	TO1 - Has the highest probability of keeping the cell and glass intact [15]	TT1 - Vulnerable to energy market fluctuations [23]
	TS2 - Possible recovery of the complete photovoltaic cell [5]	TW2 - GHG emissions [5]	TO2 - No generation of toxic effluents [23]	TT2- CONAMA Resolution 382/2006, which establishes parameters for atmospheric emissions [24]
	TS3 - Can receive a considerable volume of photovoltaic panels in the same operation	TW3 - Hydrofluoric acid (HF) emission if the backsheet is not removed [14]	TO3 - As recycling panels are costly, recycling in bulk is advantageous compared to other methods [11]	TT3 - Laboratory scale [22]
	TS4 - High integrity photovoltaic cell recovery [21]	TW4 - Requires temperature control [14]	TO4 - Growth opportunity with green heating technologies [11]	
	TS5 - High repeatability due to organic solvent not degrading [21]	TW5 - Expensive Equipment [22]	TO5 - Possible collaborations with energy industries to reduce energy costs [11]	
	TS6 - No chance of cell breakage [22]	TW6 - A very high level of operational control is required [21]	TO6 - Studies are being carried out to verify the viability of the method in second-generation modules [22]	
	TS7 - Easy glass removal even if broken [22]			

In Tables 3, 4, and 5, the indicators necessary to create a SWOT matrix were identified based on each type of treatment. However, some specifications distinguish each method, even within a single treatment category. Therefore, in Table 6, each uniquely identified treatment will match the possible

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factors mentioned. Only the acronyms for each factor were used to avoid the table becoming confusing and cluttered.

Table 5. SWOT factors compiled from possible chemical methods.

Treatment	Strengths	Weaknesses	Opportunities	Threats
Chemical	CS1 - Almost complete removal of the EVA layer [5]	CW1 - Delamination time depends on module area [5]	CO1 - Possibility of reusing the solution [11]	CT1 - It is not always possible to completely degrade EVA, being less efficient than other methods [23]
	CS2 - Solvent reuse possible [5]	CW2 - Considerably long delamination time [5]	CO2 - Possible reuse of photovoltaic cell [5]	CT2 - Due to CONAMA resolution 430/11, careful treatment of effluents is required [27]
	CS3 - Simple EVA separation [5]	CW3 - Handling of solutions hazardous to human health [5]	CO3 - Possibility of growth with research and development of less toxic and more sustainable solvents. [11]	CT3 - Expensive equipment [5]
	CS4 - Considerable acceleration of the process for a few hours [5]	CW4 - May require secondary treatment due to non-complete removal of EVA [5]		CT4 - Need for care in handling and strict safety measures due to toxicity of solvents [11]
	CS5 - Complete removal of the EVA layer [5]	CW5 - If there is no expansion control, the photovoltaic cell breaks [17]		CT5 - Vulnerable to solvent market variation [11]
	CS6 - Oxidizes the solar cell less than thermal methods [25]	CW6 - Mandatory presence of ethanol in the solution [25]		
	CS7 - No production of toxic effluents [26]	CW7 - Emission of pollutant oxides and gases [26]		
		CW8 - Formation of halogenated residues [5]		
		CW9 - Expensive equipment [26]		
		CW10 - High process control required [26]		

Table 6. Correspondence of each factor listed with each of the methods studied.

Treatment	Method	Strengths (S)	Weaknesses (W)	Opportunities (O)	Threats (T)
Physical	Hot Knife	PS1, PS2, PS3, PS4, PS5, PS6	PW1, PW3, PW4, PW5, PW7, PW8	PO2, PO3	PT1, PT3, PT4, PT5
	High Voltage Pulse	PS1, PS2, PS3, PS4, PS5, PS7	PW1, PW4, PW5, PW7	PO2, PO3, PO4	PT1, PT3, PT4, PT5, PT6
	Crushing/Grinding	PS1, PS2, PS3	PW1, PW2, PW3, PW4, PW6, PW7	PO1, PO2, PO3, PO4	PT1, PT2, PT3, PT4, PT5
	Laser	PS1, PS2, PS3, PS5, PS7	PW4, PW5, PW7, PW8, PW10, PW11	PO2, PO3, PO4	PT1, PT3, PT4, PT5, PT6
Thermal	Combustion/Pyrolysis	TS1, TS2, TS3	TW1, TW2, TW3, TW4	TO1, TO2, TO3, TO4, TO5	TT1, TT2
	Electrothermal	TS1, TS3, TS6, TS7	TW1, TW4, TW5	TO2, TO3, TO4, TO5, TO6	TT1, TT2, TT3
	Solvothermal Swelling with Thermal Decomposition (SSTD)	TS1, TS2, TS3, TS4, TS5	TW1, TW2, TW4, TW5, TW6	TO1, TO2, TO3, TO4, TO5	TT1, TT2
Chemical	Organic Solvent	CS1, CS2, CS3	CW1, CW2, CW3, CW4, CW5	CO1, CO2, CO3	CT1, CT2, CT4, CT5
	Inorganic Solvent	CS1, CS2, CS3, CS4, CS6	CW1, CW2, CW6, CW7	CO1, CO2, CO3	CT1, CT2, CT4, CT5
	Organic Solvent with Ultrasound	CS2, CS3, CS4, CS5	CW1, CW2, CW5, CW8, CW9	CO1, CO2, CO3	CT1, CT2, CT3, CT4, CT5
	Supercritical CO_2	CS1, CS2, CS3, CS4, CS7	CW1, CW3, CW5, CW9, CW10	CO1, CO2, CO3	CT1, CT2, CT3, CT4, CT5

To prepare Table 7 of factor crossings to identify at what level each method fits into the scenarios, the sum of the quantities of each factor was performed. Thus, the higher the value of each scenario, the more factors the method has that make it compatible.

Table 7. The SWOT matrix with the sum of the factors corresponding to each scenario indicates the degree of intensity.

Treatment	Method	Growth (S+O)	Maintenance (S+T)	Development (W+O)	Survival (W+T)
Physical	Hot Knife	6S + 3O = 9	6S + 5T = 11	6W + 3O = 9	6W + 5T = 11
	High Voltage Pulse	6S + 4O = 10	6S + 5T = 11	4W + 4O = 8	4W + 5T = 9
	Crushing/Grinding	3S + 4O = 7	3S + 5T = 8	6W + 4O = 10	6W + 5T = 11

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	Laser	5S + 3O = 8	5S + 5T = 10	6W + 3O = 9	6W + 5T = 11
Thermal	Combustion/Pyrolysis	3S + 5O = 8	3S + 2T = 5	4W + 5O = 9	4W + 2T = 6
	Electrothermal	4S + 6O = 10	4S + 3T = 7	3W + 6O = 9	3W + 3T = 6
	Solvothermal Swelling with Thermal Decomposition (SSTD)	5S + 5O = 10	5S + 2T = 7	5W + 5O = 10	5W + 2T = 7
Chemical	Organic Solvent	3S + 3O = 6	3S + 5T = 8	5W + 3O = 8	6W + 5T = 10
	Inorganic Solvent	5S + 3O = 8	5S + 5T = 10	4W + 3O = 7	4W + 5T = 9
	Organic Solvent with Ultrasound	4S + 3O = 7	4S + 5T = 9	5W + 3O = 8	5W + 5T = 10
	Supercritical CO_2	5S + 3O = 8	5S + 5T = 10	5W + 3O = 8	5W + 5T = 10

4. Discussion

When analyzing Tables 6 and 7, it was possible to observe that:

Growth:

For different reasons, the three types of treatments have similar values on average, with preference given to thermal treatments (9.3), physical therapies (8.5), and chemical treatments (7.25).

Chemical and physical treatments have more strengths than opportunities, indicating that despite being methods with many advantages, they are not as strong as thermal treatments and/or do not have as much opportunity to grow in the current Brazilian scenario.

Thermal treatments, therefore, have greater or equal opportunities concerning their strengths, indicating that, on average, they have a greater possibility of growth due to their advantages and favorable environment.

The methods that present the most excellent chance of growth among the treatments mentioned were High voltage pulse, Electrothermal, and SSTD.

Maintenance:

In this scenario, the averages that have similar values are only for chemical (9.25) and physical (10) treatments, while heat treatment (6.3) has lower values.

This is justified because, despite having well-established strengths, chemical, and physical treatments have more significant difficulties with external environmental and market factors due to major problems with expensive equipment and toxic waste/effluents.

On the other hand, heat treatments do not have as many barriers because they have simple equipment (mainly), and, as they emit GHGs during operation, they do not pose as many threats. Therefore, heat treatment is the one that least fits into a maintenance scenario.

The methods that present the greatest need for maintenance to eliminate threats are Hot knife and High voltage pulse.

Development:

Once again, the three types of treatment have similar arithmetic averages, in order from best to worst: heat treatment (9.3), physical treatment (9.0), and chemical treatment (7.75).

Although both development and growth seem similar in concept, there is one crucial factor that development can indicate: the opportunity to eliminate weaknesses. This is explained by the fact that despite always being categorized as the weakest, physical treatments are superior to chemical treatments since they have more opportunities to eliminate their weaknesses.

Many physical treatments are still in the laboratory phase and may be able to develop to eliminate their many weaknesses. Chemical treatment, despite not having as many weaknesses, is already well established and does not have as many development opportunities.

Heat treatment is at the forefront of this sector because it still has good opportunities for growth and development but has few weaknesses compared to the other treatments.

The methods with the most significant room for development are Crushing/Grinding and SSTD.

Survival:

In this scenario, chemical (9.75) and physical (10.5) treatments have similar average values. Since the survival scenario is negative, the less a technique identifies with it, the less critical its conditions will be. The treatment that scores the lowest on average in this scenario will be superior to the others, and in this case, thermal treatment presented an accumulated value of 6.3.

Therefore, given the current Brazilian environment, a thermal method has the greatest chance of survival among the three, since it has the fewest weaknesses and threats. This shows that physical and chemical methods may not have viable uses depending on the situation and location.

The methods that need to be reassessed for application are hot knife, crushing/grinding, and laser.

Based on the assessment of the four scenarios, it can be said that, in general, physical and chemical treatments, regardless of the method, have had the most significant difficulty in establishing themselves in Brazil. However, this does not mean they should be discarded entirely since they have sufficient development to overcome their weaknesses and threats and become more viable treatment methods.

Heat treatment, therefore, becomes the most prominent in the choice of any method for delamination of photovoltaic modules, remaining preferably in the first place, positive in all scenarios examined. Most heat treatment methods are already commercialized, produce few toxic elements, and require practically only equipment and energy (rarely requiring inputs), a significant factor in their strength in Brazil.

Based on a more detailed assessment, it is possible to highlight which specific methods would be the most advantageous for the Brazilian scenarios. Therefore, the growth scenario is the most favorable since it only has positive factors.

5. Conclusions

It was possible to identify that some photovoltaic panel recycling methods have certain advantages. However, as it was possible to observe, each method highly depends on local operating conditions.

Although not absolute, the SWOT analysis provided a good understanding of the recycling methodologies for this type of material for the current Brazilian reality. The indication of their advantages and disadvantages, as well as their opportunities and threats, can also instigate solutions to the main problems of these methods.

Considering the Brazilian reality, in which it is not yet possible to recycle solar panels on a large scale, heat treatment would be the most appropriate, with the SSTD and Electrothermal methods being the most promising. This is because they have the best results presented in the methods discussed in the SWOT analysis. Therefore, these heat treatments can be considered high recovery methods for reusing components, depending only on an already established energy matrix, generating fewer operating problems.

Through the SWOT analysis, it was concluded that, for the adoption of each method, there are predefinitions that must be respected. Although the SSTD and Electrothermal methods are considered more appropriate in a general Brazilian context, the choice of a method depends on factors such as location, budget, quantity of modules to be recycled, quality of operation, etc. Each method has specific advantages, and no method is superior.

Due to the laws and regulations established in Brazil and the environmental impact of improper disposal of WEEE, the severity of defining a standard route for recycling photovoltaic modules is conclusive. Given the lifespan of a photovoltaic panel, a large flow of panels for disposal has already

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occurred this year in Europe. Since Brazil began to experience its growth in photovoltaic energy around 2013, it is expected that, in 14 years, there will be an exuberant amount of waste requiring proper disposal.

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