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Original Article

Study, qualitative-quantitative analysis, and sizing of the environmental impact of the photovoltaic panel recycling process

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Abstract. This study investigates the efficiency and environmental impact of photovoltaic panel recycling processes through qualitative and quantitative analyses, focusing on three case studies in Peru. The research addresses the pressing problem of solar panel waste management at the end of their useful life; this aspect is of particular importance due to the current boom in renewable energies. The first case study concerns a group of 5 rural houses in Puno consuming 10 kWh/day. The second case examines the rooftop PV system of the Institute of Mining Engineering of Peru, with a capacity of 20 kW. The third case explores the Rubi solar power plant in Moquegua, with a capacity of 179.5 MW. The qualitative analysis details the sub-processes involved in solar panel recycling, while the quantitative analysis evaluates the energy payback time (EPBT) for each case. In addition, the study evaluates the environmental impact by measuring the total carbon footprint of the recycling processes. The results reveal the ratio in terms of carbon footprint of the panel recycling process to the total lifetime of the panel. This research provides a novel perspective on the use of photovoltaic panels as renewable energy and suggests future avenues for improving recycling technologies and policies.

Keywords: Photovoltaic cycle / energy payback time (EPBT) / carbon footprint / photovoltaic panels / recycling

1 Introduction

Historically, technological advances have constantly transformed industries and social paradigms. We are currently experiencing the aftermath of the third industrial revolution, characterized by electronic miniaturization and technological globalization. While these advances have driven progress, they have also increased the demand for resources and energy, leading to significant environmental problems.

Forecasts indicate that by 2035 global energy demand will double to 778 exajoules (EJ) [1]. This poses a major challenge, as the current energy infrastructure may prove insufficient to meet this demand in a sustainable manner. Moreover, if immediate action is not taken, greenhouse gas emissions could increase by 50% by 2050, which could raise the global average temperature by up to 6 °C [2]. These changes would have serious consequences, such as extreme weather events, loss of biodiversity, water scarcity and rising sea levels.

Faced with this problem, the use of renewable energies such as photovoltaics is presented as a solution. In fact, in the last decade, the market for photovoltaic (PV) panels has expanded significantly, driven by global initiatives promoting renewable energy technologies [3]. Despite the clear benefits of solar energy, the rapid growth of PV installations has drawn attention to their environmental impact, especially in terms of waste management and resource use [4].

Given this premise, the key question around which this research revolves is: to what extent is the energy clean throughout its lifetime, and to what extent is it clean at the end of the lifetime of a PV panel installation? Does it really justify its use as truly clean renewable energy?

Faced with this dilemma, this study aims to address the critical issue of PV panel waste management by assessing the efficiency and environmental impact of recycling processes. The research focuses on three case studies in Peru, covering different scales and contexts of PV installations; these three cases have been previously selected in a related study that focuses on the whole PV Cycle process [5,6], this will ensure continuity to the main investigation. Through qualitative and quantitative analyses, this study investigates existing recycling methodologies, identifies research gaps, and proposes improvements to increase the sustainability of solar energy systems.

The results of this research are expected to provide valuable information for optimizing PV panel recycling practices. By measuring the energy payback time (EPBT)

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and total carbon footprint of recycling processes, this study provides a comprehensive assessment of the environmental benefits and challenges associated with PV panel recycling. Ultimately, the goal is to inform policy and promote practices that support a sustainable energy transition in Peru and beyond.

Assessing the carbon footprint at the end-of-life management stage remains highly relevant for several reasons. Even if results show that emissions at this stage are insignificant, understanding them ensures a comprehensive lifecycle analysis. This detailed assessment captures the full environmental impact of photovoltaic panels, leaving no stage unexamined.

Furthermore, the end-of-life stage presents opportunities for optimizing recycling processes. Improvements in this area can lead to further reductions in emissions and more efficient resource use, thereby enhancing the overall sustainability of photovoltaic technology.

Additionally, detailed assessments at this stage can guide the development of better practices and policies for end-of-life management. By identifying areas where emissions can be minimized, industry leaders and policymakers can establish guidelines that promote greener recycling and waste management practices.

Finally, transparency in reporting emissions at all lifecycle stages, including end-of-life, is crucial for building consumer and stakeholder trust. It supports informed decision-making for consumers, investors, and regulatory bodies, highlighting the commitment to environmental responsibility.

Therefore, while emissions at the end-of-life stage might be relatively low, their assessment is essential for a holistic approach to sustainability in the photovoltaic industry.

1.1 Environmental general issue snapshot

Due to the environmental general issue mentioned above, initiatives, regulations, and treaties have been implemented at the international level to regulate and mitigate the effects of climate change. A prominent example is the “Paris Agreement”, signed in 2015, which seeks to limit global warming to less than 2 °C above pre-industrial levels [2]. However, despite these efforts, it is recognized that current measures are not sufficient to achieve this goal. The recent 26th meeting of the Conference of Parties (COP26), known as “The Last Chance Saloon” [7,8], has been considered as the last chance to take meaningful action and avoid the worst effects of climate change.

At the national context, Peruvian regulations and initiatives have also been enacted to address environmental issues and promote the use of renewable energies, including photovoltaic. Notable initiatives include incentives and subsidies for the installation of solar panels in homes and businesses, as well as the implementation of community solar energy programs [9]. These programs allow residents to join and share the benefits of solar generation, promoting access to renewable energy in communities that would otherwise be unable to access it.

This environmental issue raises the need for sustainable solutions, and photovoltaic panels present themselves as a priori option to address it. However, it is important to recognize that there is a mis- perception that PV panels are completely “green”. Just like any other electronic tool, from production to commissioning and end-of-life, PV panels have an energy consumption and therefore an associated carbon footprint.

While it is true that the generation of solar energy through photovoltaic panels does not produce direct greenhouse gas emissions during operation, the manufacturing and assembly stage involves the use of natural resources, energy and industrial processes that can generate emissions and waste. The extraction and production of the materials needed to manufacture the photovoltaic panels, such as silicon, requires energy and can have significant environmental impacts, such as water and soil pollution [4–6].

In addition, during the installation of PV panels, energy is required for transportation, assembly, and connection to the grid, in the case of ON-GRID systems [10].

On the other hand, at the end of their useful life, PV panels must be properly managed for recycling or final disposal. The solar panel recycling process is still under development and faces specific technical and economic challenges. Technical challenges include the complex disassembly of panels made of diverse materials such as glass, aluminum, and silicon, which are common in the over 90% of panels available in market, specifically which are based on crystalline silicon (c-Si) technology cells (or first-generation cells) [11]. In a smaller portion of the market, cadmium is present, specifically in CdTe panels. In both scenarios, hazardous metals like lead, used in nearly all PV panels, and cadmium, require efficient separation and recovery through advanced technologies such as thermal, chemical, and mechanical processes, which are not always widely available or cost-effective. Economically, recycling solar panels can be expensive due to these sophisticated processes and the relatively low initial volumes of panels being recycled. Improper management of this process could result in a significant amount of waste, including potentially hazardous materials, exacerbating environmental concerns.

1.2 Preliminary aspects

First, in relation to the environmental impact assessment of PV panels, the four stages of the PV chain were considered: preplanning and design, construction, operation, and maintenance, and dismantling and recycling [12].

However, the analysis focuses on the final stage of the chain, the recycling of PV panels. Furthermore, the study is limited to the PV panel as a technology, without considering additional components that depend on the type of PV installation (grid-connected, off-grid, hybrid), such as batteries, inverters, and charge controllers [10], this is due to the complexity, extension, and main objective of the research work.

Regarding the current PV panel market, there is a constant update and evolution that has resulted in four different generations of panels available today [13]. However, the analysis was based on first- and second-generation panels, mainly composed of polycrystalline silicon (poly-Si), due to their presence in the market both locally and internationally [14,15], compared to the latest PV panel technologies, the current demand and their predominance in installations and panels that are close to being recycled based on their useful life period.

1.3 PV recycling

The solar panel recycling process consists of several key steps, each of which plays an important role in recovering valuable materials and minimizing waste. The following are the stages of recycling and the materials involved in each stage.

1.3.1 Panel disassembly

In this stage, the solar panels are uninstalled and disassembled. Aluminum frames, electrical cables and other unwanted components are removed. These secondary materials, such as frames and cables, are sorted for further processing and separate recycling [16,17].

1.3.2 Delamination stage

Delamination involves the separation of the layers that make up the solar panel. Photovoltaic panels typically consist of layers of glass, metal, plastic, and solar cells. Depending on the method used, either thermal, mechanical, or chemical, the separation of these layers takes place. For example, in the thermal method, the panel is subjected to high temperatures to peel off the layers, whereas, in the mechanical method, grinding or cutting tools and processes are used to separate the different layers [16,17].

1.3.3 Metal recovery

Once the layers have been separated, the recovery of valuable materials proceeds. At this stage, metals such as silicon, which is a key component in solar cells, as well as other precious materials such as silver, copper, and aluminum, are sought to be extracted. These materials can be recovered by various methods, such as shredding, magnetic separation and flotation, among others [16,17].

1.3.4 Sorting and preparation for reuse or final disposal

After recovery of valuable materials, the components are sorted into different categories according to their quality and prepared for reuse or final disposal. Some materials may be reconditioned and reused in the manufacture of new solar panels or other electronic products, while others may require further treatment or be sent to appropriate disposal facilities [16,17].

It is important to note that there are different approaches and methods for carrying out each stage of the solar panel recycling process. For example, in the delamination stage, in addition to the methods mentioned above, new technologies and approaches are also being investigated, such as the use of specific chemical solvents to separate the layers more efficiently and with less environmental impact.

While some of these solar panel recycling processes have been implemented at the industrial and commercial level, others are still in a state of experimentation or development in laboratories and research centers. Therefore, for the analysis carried out, the route and procedures described above have been taken into consideration as a reference, since they represent a consolidated and reliable methodology in the photovoltaic panel recycling industry.

Regarding the current PV panel market, there is a constant update and evolution that has resulted in four different generations of panels available today [13]. However, the analysis focused more on polycrystalline silicon (poly-Si) panels rather than monocrystalline silicon panels. This is because poly-Si technology has a higher presence both locally and internationally, driven by its cost-effectiveness and widespread adoption. Consequently, poly-Si panels dominate installations and are more likely to reach the end of their useful life sooner, making them the primary candidates for degradation and recycling studies.

2 Methodology

2.1 Study cases

Three case studies representing different levels of energy consumption were analyzed in this study. These cases will be taken from a previous analysis that focuses on the entire life cycle of the PV panel, considering the rest of the PV cycle [5,6]. The choice of these cases is based on the consumption levels in each case, since energy consumption has an important value in the evaluation. Finally, it is important to note that solar installations in Peru are becoming more viable due to the specific constraints of different regions. Therefore, this topic is becoming increasingly important to study [18].

2.1.1 Case study 1: low consumption

The first case study focuses on a group of five rural households located in Puno, which have an approximate consumption of 10 kWh per day. This amount of electricity is sufficient to cover the basic lighting, household appliances and communication needs of these families. In this context, the experience of an Italian company, Ergon Perú S.A.C., belonging to the Tozzi Green group, which is responsible for the supply of electricity through renewable energy resources in areas without access to the electricity grid, was considered. For this case, it was considered that 120 Wp solar panels are used in domestic installations [5,6], detailed information of the panel could be found in [19].

2.1.2 Case study 2: average consumption

The second case study focuses on the PV system installed on the roof of the Institute of Mining Engineers of Peru. This system has a nominal capacity of 20.8 kW and uses solar panels of 400 Wp nominal power each. The implementation of the system was carried out by ENGIE Peru, and two Peruvian companies, Novum Solar and Deltavolt, in charge of importing solar panels, were consulted to select the assembly company. For this case, as mentioned in [5], the panels of the supplier Canadian Solar are the ones selected as the object of study in this case.

2.1.3 Case study 3: high consumption

The third case study refers to the Rubi Solar Power Plant in Moquegua. This plant has a nominal generating capacity of 179.5 MW in direct current and is composed of 560,880 solar panels of 320 Wp nominal power each. According to the information provided by ENEL Peru, the concessionaire, the solar panels used come from Risen Energy, a Chinese company with vendors in the United States. In this case, it is understood that ENEL Peru established direct contact with the U.S. headquarters due to the volume of panels required for the solar plant [5,6].

These three case studies represented different levels of energy consumption, from low consumption rural homes to a large-scale solar power plant. The analysis of these cases provided relevant information on the management and recycling of photovoltaic panels in different contexts and will contribute to the global understanding of the environmental issues associated with this technology.

2.2 EPBT and carbon footprint

Energy Payback Time (EPBT) is the period required for an energy generation system or technology to generate the same amount of energy as that used in its production, installation, maintenance, and decommissioning/recycling.

When applied to photovoltaic panels, EPBT specifically refers to the time required for the energy generated by a solar panel to equal the total energy used in its life cycle. This includes the energy required to extract and process the raw materials, manufacture the panel components, transport it, install it, maintain it, and finally dismantle or recycle it.

The EPBT is calculated by dividing the total energy embodied in the panel (input energy) by the energy generated annually by the panel (output energy). The input energy represents the total energy consumption over the life cycle of the panel, while the output energy is the amount of electrical energy that the panel can produce for one year, thus giving the EPBT expressed in years. The general expression defining the EBPT is shown in equation (1).

$$EPBT_{Years} = \frac{E_{input}}{E_{output}}. \tag{1}$$

In addition, it is possible to break down the EPBT concept by identifying the internal processes that are associated with it, i.e. in which energy consumption occurs; these processes are as follows:

1. Material procurement energy: This represents the energy required to extract and process the raw materials used in the manufacture of the photovoltaic panels, such as silicon, glass, and metals.
2. Manufacturing energy: This corresponds to the energy used during the panel manufacturing process, including silicon cutting and doping, solar cell manufacturing, encapsulation, frame manufacturing and other components.
3. Energy for transportation of panels to the installation site: Involves the energy required for the transportation of the photovoltaic panels from the manufacturing facilities to the site where they will be installed, considering land, sea, or air transportation.
4. Installation and commissioning energy: Represents the energy required for the physical installation of the panels at the designated site, including the installation of supports, electrical connections, and operational testing.
5. End-of-life management and recycling (EOL) energy: Involves the energy required to dismantle or recycle the PV panels at the end of their useful life, including collection, transportation, and processing of the materials for subsequent reuse or proper disposal.

Thus, the complete formula can be expressed as equation (2).

$$EPBT_{Years} = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{E_{output}}. \tag{2}$$

E_{mat}: Energy required to process and obtain materials for a PV panel;
E_{manuf}: Energy required to manufacture a PV panel;
E_{trans}: Energy required to transport a manufactured PV panel;
E_{inst}: Energy required to install a PV panel once in installation place;
E_{EOL}: Energy necessary for end-of-life management for a PV panel;
E_{OUTPUT}: Energy that a PV panel produce in a period of time (e.g. per year).

In reference to the management at the end of the useful life of the panel, it is crucial to know the EPBT itself since although the calculation is made on the entire photovoltaic chain, it is important to know the degree of energy efficiency in recycling in relation to the complete process, this helps to understand the link in the chain that should be prioritized in terms of the relationship between energy efficiency and carbon footprint.

Carbon footprint is a measure of environmental impact in terms of greenhouse gas (GHG) emissions associated with a product, activity, or event. In the case of photovoltaic panels, carbon footprint refers to the amount of GHG emissions generated during the entire life cycle of the panel, including its manufacture, transportation, installation, use and final disposal.

The calculation of this parameter consists on obtaining the GHG emissions, in terms of tons of CO_2 (tCO_2 eq), associated with some process or activity using already established conversion tables, this information is provided by [20] that states the carbon footprint associated with energy consumption by electricity sources, intended for renewable energy investment projects in the Peruvian context.

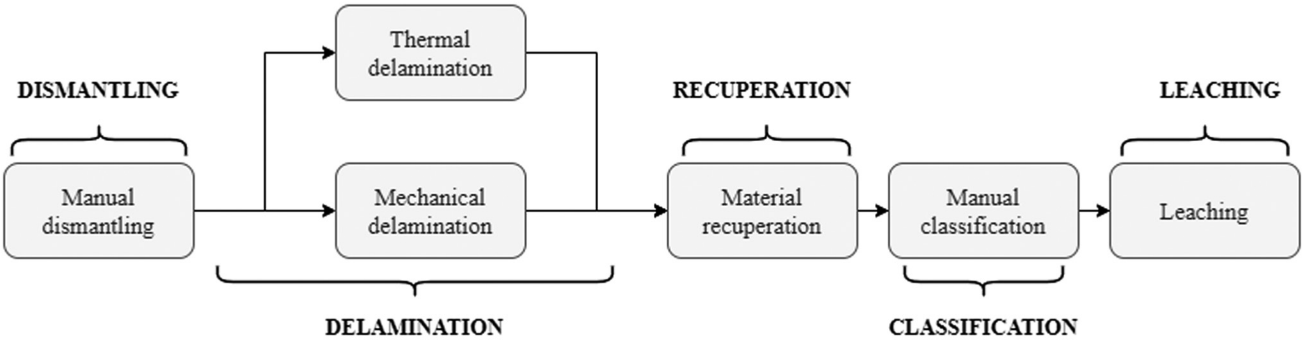

Fig. 1. PV Recycling process [17].

3 Qualitative-quantitative analysis

3.1 Qualitative analysis

As indicated above, it is necessary to focus the EPBT calculation on the life cycle of photovoltaic panels in their final stage of life; in this sense, the objective of the qualitative analysis was to identify the subprocesses and variables that allow the energy balance in the recycling process of photovoltaic panels. The processes identified according to the reviewed documentation [16,17] and on which the EPBT calculation will be subsequently performed are presented in Figure 1.

- Dismantling: In the dismantling stage, the average consumption of the tools used during the procedure is considered. In addition, human caloric energy consumption is considered based on data provided by [21], which refers to the number of operators in charge of dismantling for the whole PV cycle. It also provides relevant information to calculate the calories consumed per operator in each case. These data are used to estimate the human caloric energy consumption in the dismantling stage. Both the energy consumption of the tools used, and the human caloric consumption are considered, with the objective of calculating the total energy consumption in this phase of the PV panel recycling process.
- Delamination: The delamination process in PV panel could be reached by two approaches: mechanical delamination and thermal delamination. Mechanical delamination is carried out by the milling/grinding technique, using tools such as the Retsch SM 2000, which has a rated power of 2.2 kW. According to Restch's test report, the capacity of this tool is 0.14 h/kg [22]. With this information, the total number of working hours required to process all the panels in the main recycling chain is calculated, and from that, the total energy consumption during the mechanical delamination phase can be determined. On the other hand, thermal delamination uses the leaching direct pyrolysis technique to separate the panel materials. In this process, energy consumption is estimated using the concept of specific heat for each of the relevant and most abundant elements in the panel, such as EVA encapsulation, glass and silicon. These elements and their weight proportions in the panel are known data. To calculate the energy consumption of this stage, the operating temperature, the treatment time and the specific heat of each material are multiplied, considering their proportional amounts to the total weight of the panel [16,17]. In this specific case, for the calculation of the EPBT, the process that incurs the highest energy consumption will be taken, since both techniques are valid in the recycling process.
- Materials recovery: In the materials recovery stage, the transformation of silicon wafers into porous silicon, a material widely used in the manufacture of solar panels, is carried out. To achieve this, a silver and aluminum removal process is required using nitric acid (HNO_3) and hydrochloric acid (HCl), respectively. Each removal takes approximately 1.5 hours and is performed using an ultrasonic cleaner with a power of 150 W. Once the total removal time of both materials has been estimated, it is possible to calculate the energy consumption of this stage as a function of the time and power used [16,17].
- Classification: In the manual sorting stage, the energy effort of the operators was considered, which is similar to that of the dismantling stage, but with a light work caloric load. However, the number of working days will vary, this is due to the number of operators in charge of sorting. To quantify the number of shifts, the number of operators involved in sorting will be considered. With this information, it will be possible to determine the energy workload and estimate the number of days required to complete the manual sorting stage [16,17].
- Leaching: In the leaching stage of the PV panel recycling process, the objective is to dissolve specific components from the crushed and pre-treated panel materials using chemical solutions. This process is typically employed to extract valuable metals such as silver, aluminum, and lead. The leaching process involves several steps, which include the preparation of the leaching solution and the actual leaching operation [16,17].

Once the processes were described and analyzed, it was possible to break down again the EPBT of the recycling process according to the subprocesses already

Table 1. Study cases analysis.

Parameter	Case I	Case II	Case III
PV panels technology	Poly-Si	Poly-Si	Poly-Si
[P.N] Number of panels in each case	22	52	560880
[R.P] Required Power (MW)	0.0020	0.0208	179.5
[N.P] Nominal Power per panel in each case (Wp)	120.0	400.00	320.0
Solar Cell Length (mm)	156.750	–	156
Solar Cell Width (mm)	156.750	–	156
Number of Cells per panel	36	120	72
[P.W] Panel Weight (kg)	8.50	21.00	26.00
Panel Efficiency	15	21.1	17.5
Annual Irradiation Ratio (AIR) (kWh/m^2)	2374.60	1785.30	2735.90
Panel Length (m)	1.130	1.754	1.956
Panel Width (m)	0.668	1.096	0.992

identified. Thus, the EPBT focused on recycling is defined by equation (3):

$$EPBT_{EOL} = \frac{E_{dis} + E_{del} + E_{rec} + E_{cla} + E_{lea}}{E_{OUTPUT}}. \tag{3}$$

E_{dis}: Energy involved in dismantling process;
E_{del}: Energy involved in delamination process;
E_{rec}: Energy involved in recovery stage process;
E_{rec}: Energy involved in classification process;
E_{cla}: Energy involved in leaching process.

3.2 Quantitative analysis

The detailed characteristics and specifications of case studies 1, 2 and 3 are presented below. Regarding cases 1 and 3, to ensure the accuracy of the data and the characteristics of the PV panels used in each case, reference was made to the data sheets of the panels from the documentation corresponding to the case [23,24]. As for case study 2, the characteristics of the installation were considered based on the supplier and the PV panel series of the ENGIE company, which is also responsible for the concession for the installation of the panels in case study 2 [25]. A panel array with a rated power of 400 Wp is used.

On the other hand, the annual irradiation ratio in each of the case studies was defined by the location of the installation and based on the Global Solar Atlas [26]. In the low consumption case study, the solar panel supplier Energon, belonging to the Tozzi Green group, was chosen, and panels of Italian origin with a nominal power of 120 Wp were used, which is the power used for this type of installation according to the supplier.

For the medium consumption case, ENGIE was also in charge of the concession and 400 Wp panels with the already mentioned characteristics were considered [5,6]. In the case of high consumption, corresponding to the Rubi solar power plant, the data provided by ENEL Peru was considered, ensuring that panels with nominal power of 320 Wp were provided by Risen Energy, this nominal power could be obtained as part of the technical report for another installation from the supplier of these panels [27]. As part of the quantitative analysis (EPBT calculation), Table 1 shows the main and most relevant characteristics found for the three case studies taken into consideration for the analysis.

Once the parameters have been identified in each case study, the energy consumption was calculated for each subprocess previously indicated. As a note for the following tables, values that are shared between the case studies are slightly highlighted.

Table 2 presents dismantling stage energy consumption (MJ) for each case.

The total energy consumption for the mechanical dismantling stage is subdivided as sum of energy consumption by human effort and by use of tools for dismantling, an important observation is that in the case of low consumption the consumption by tools is higher than the consumption by human effort, while in the cases of medium and high consumption this relation is inverted.

Table 3 presents mechanical delamination stage energy consumption (MJ) for each case.

For the mechanical delamination stage, the energy consumption is directly proportional to the production capacity in each case study.

Table 4 presents thermal delamination stage energy consumption (MJ) for each case.

For the thermal delamination stage, the resulting energy consumption is defined by a summation for the materials with the highest presence in the photovoltaic panel, considering the percentage of presence, the specific heat of each material and the treatment time of the materials, an important aspect to consider is that the 3 materials with the highest presence are glass, EVA and silicon. Additionally, as mentioned above, since the delamination technique associated with the highest energy consumption was mechanical delamination, this will be the one taken into account for the EPBT and carbon footprint calculation.

Table 5 presents materials recovery stage energy consumption (MJ) for each case.

For the material recovery stage, the energy consumption is directly proportional to the production capacity in each case study.

Table 2. Dismantling stage.

Parameter	Case I	Case II	Case III
a. Number of workers	2	24	300
b. Average Nominal Power per Tool Use (W)		1250	
c. Number of Hours per Panel for Disassembly (h)		1	
* Number of total hours for disassembly per case ([P.N] * c.)	22.00	52	560,880
* Number of workdays based on time (workday-8h) (([P.N] * c.) ÷ 8)	2.75	6.50	70,110
d. Caloric Consumption Factor (kcal/8hr-workday)		2000	
* Total caloric consumption per case (kcal) (a. * (([P.N] * c.) ÷ 8)) * d.)	11000.00	312000.00	4.21E+10
* Total Caloric Consumption (MJ) ((a. * (([P.N] * c.) ÷ 8)) * d.) * $K_{kcal\text{-}MJ}$)	46.02	1,305	1.76E+08
* Dismantling stage tools total consumption (kWh) ([P.N] * b. *c.)	27.50	65	7.01E+05
* Total Energy Consumption per tools (MJ) (([P.N] * b. *c.) * K $_{\text{kWh-MJ}}$)	99.00	234	2.52E+06
Total Consumption for dismantling (MJ)			
(Total Caloric Consumption + Total Energy Consumption per tools)	**145.02**	**1,539.41**	**1.79E+08**

Table 3. Delamination stage (mechanical).

Parameter	Case I	Case II	Case III
a. Machinery Power – SM200 Retsch (kW)		2.2	
b. SM 200 Retsch – Material Processing Capacity (kg)		0.60	
c. SM 200 Retsch – Processing Time (h)		0.08	
* Capacity of SM 200 Retsch (h/kg) (c. ÷ b.)		0.14	
* Energetic consumption per panel (kWh/kg) (a. * (c. ÷ b.))		0.31	
* Total consumption (kWh) ([P.N] * [P.W] * a. * (c. ÷ b.))	57.14	333.67	4.46E+06
Total consumption for mechanical delamination (MJ) ([P.N] * [P.W] * a. * (c. ÷ b.)) * $K_{kWh\text{-}MJ}$	**205.70**	**1,201.20**	**1.60E+07**

Table 4. Delamination stage (thermal).

Parameter	Case I	Case II	Case III
Pyrolysis Treatment Time per Panel [h]		0.5	
Required Operating Temperature per Panel [°C]		650	
Average Encapsulated EVA Specific Heat [kJ/kg °C]		2.3	
Average Glass Specific Heat [kJ/kg °C]		1.68	
Average Silicon Specific Heat [kJ/kg °C]		0.84	
EVA Weight Percentage [%]		7%	
Glass Weight Percentage [%]		75%	
Silicon Weight Percentage [%]		3%	
Total consumption for thermal delamination (MJ)	**9.31E+02**	**5.44E+03**	**7.26E+07**

Table 5. Recovery stage.

Parameter	Case I	Case II	Case III
a. Time for Silver and Aluminum Removal in HNO_3 (h)		1.5	
b. Time for Silver and Aluminum Removal in HCl (h)		1.5	
c. Ultrasonic Cleaner Power (W)		150	
* Recovery energy consumption per panel (kWh) (c. * (a. + b.) ÷ 1000)		0.45	
* Total Consumption for Recovery (kWh) ([P.N]* c. * (a. + b.) ÷ 1000)	9.900	23.40	2.52E+05
Total consumption for Recovery (MJ) ($K_{kWh\text{-}MJ}$ *[P.N] * c. * (a. + b.) ÷ 1000)	**35.640**	**84.24**	**9.09E+05**

Table 6. Classification stage.

Parameter	Case I	Case II	Case III
Energy Consumption per Workday (kcal)	4,000.00	4.80E+04	2.19E+08
Number of Workdays	1	1	365
Total consumption for manual sorting (MJ)	**1.67E+01**	**2.01E+02**	**9.16E+05**

Table 7. Leaching stage.

Parameter	Case I	Case II	Case III
Ambient Temperature (°C)		25	
Solution Volume (L)		50	
Average Process Time (h)		2	
Process Efficiency		80%	
Power Required in process per panel (W)		500	
Energy Consumption per Leaching per Panel (kWh)		40	
Total Consumption for Leaching per Case (kWh)	1,375.00	3,250.00	3.51E+07
Total Consumption for leaching (MJ)	**4,950.00**	**11,700.00**	**1.26E+08**

Table 8. EPBT evaluation.

EPBT	Case I	Case II	Case III
Total Required Energy (MJ)	6.08E+03	1.90E+04	3.79E+08
Total produced Energy (MJ)	1.70E+04	1.08E+05	1.50E+09
EPBT(Years)	**0.3568**	**0.1748**	**0.2527**

Table 6 presents classification stage energy consumption (MJ) for each case.

For the sorting stage, energy consumption is considerably high compared to the previous stage, mainly due to human participation in consumption.

Table 7 presents leaching stage energy consumption (MJ) for each case.

For the leaching stage, a relatively considerable energy consumption is observed, the main variable that influences this result, considering that most variables remain constant, is the amount of material by weight that is processed in each case (or number of photovoltaic panels).

Finally, the EPBT factor according to equation (3) was calculated. The results obtained are shown in Table 8.

Table 9. Carbon footprint evaluation.

PROCESS – C.F (1.26E-04 tCO_2 eq/MJ)	Case I	Case II	Case III
DISMANTLING			
Energy Consumption by Human Labor (MJ)	46.02	1305.41	1.76E+08
Energy Consumption by Tool Use (MJ)	99.00	234.00	2.52E+06
DELAMINATION			
Energy Consumption for Thermal Delamination (MJ)	9.31E+02	5.44E+03	7.26E+07
Energy Consumption for Mechanical Delamination (MJ)	205.70	1201.20	1.60E+07
MATERIAL RECOVERY			
Total Consumption for Recovery per Case (MJ)	35.64	84.24	9.09E+05
CLASSIFICATION			
Total Consumption (Manual Sorting) (MJ)	1.67E+01	2.01E+02	9.16E+05
LEACHING			
Total Consumption for Leaching (MJ)	4,950.00	1.17E+04	1.26E+08
TOTAL CARBON FOOTPRINT (tCO_2 eq)	**0.77**	**2.39**	**4.78E+04**

3.3 Sizing of the environmental impact in terms of carbon footprint

Once the Energy Payback Time (EPBT) has been obtained and the sub-processes involved in the recycling of photovoltaic panels have been identified, the total energy consumption associated with these sub-processes was calculated. For this purpose, conversion factor of 0.4521 tCO_2 eq/MWh (1.26E-04 tCO_2 eq/MJ) obtained from [20] is used to estimate the amount of greenhouse gas (GHG) emissions generated during the entire life cycle of the panel.

The sizing results as well as the conversion factors that were used are shown in Table 9.

4 Discussion of results and perspectives

- Although the research focused mainly on the final phase of the life of photovoltaic panels, it is relevant to point out the existence of current studies that address the various stages of their life cycle [5,6]. The results of these studies show that the EPBT obtained is considerably higher in the total life cycle string of the photovoltaic panel compared to the final EPBT resulting from the present study, this consideration becomes of great importance, as it suggests that the comprehensive Life Cycle Analysis (LCA) of PV panels results in an even higher overall Energy Payback Period (EPBT). This approach provides a broader perspective than that offered by manufacturers, whose stated lifetimes are often shorter when considering actual conditions of use. This finding raises significant opportunities for future research and development of more sustainable solar energy technologies.
- For future work derived from this study, the analysis of the premature degradation of PV panels is proposed. It has been observed that the efficiency of these panels gradually decreases over the years due to natural degradation, PV panel materials and installation conditions, as revealed by documented studies. In fact, these studies show that the natural degradation of PV panels implies a reduction in efficiency of at least 1.2% per year, which limits the lifetime of the panels to approximately 10 years [28–33]. This means that the energy yields ideally obtained could be adjusted to reflect reality. This type of study will require a more extensive analysis that considers statistics and other metrics to adjust the values obtained to reality.
- Future research could deepen the technical analysis of the components surrounding the PV panel, such as inverters, charge controllers and batteries, which have their own environmental impact that should also be considered. The components of PV installations vary from each other depending on the type of installation, which means a different impact depending on the type of installation, as reviewed in [34].
- Future studies could delve into other environmental indicators, particularly focusing on the toxicities and ecotoxicities associated with the recycling processes of PV panels. Understanding these impacts comprehensively can provide a more holistic assessment of the environmental footprint of solar energy technologies.
- In an international context, the countries of the European Union actively support the use of photovoltaics as a clean and sustainable energy source. In fact, in October 2022, the European Commission approved the creation of a new European Solar Industry Alliance, which aims to support projects focused on the energy transition in Europe, thus increasing the annual market in the European Union by almost 60% to more than 40 GWp in 2022 [35]. Even in past years, despite COVID 19–pandemic, PV panel's annual market continued its moderate growth in the European Union (EU27) to about 18.2 GW in 2020 [36]. Therefore, research such as this provides valuable information for energy policies in these countries, highlighting the need to address the carbon footprint throughout the PV chain, including panel production and recycling.
- In the national context, it is crucial to recognize the ongoing efforts of decision makers to implement PV solutions as part of sustainable initiatives. While these efforts reflect a valuable commitment to sustainability, it is imperative to prioritize decision-making based on

feasibility studies and analysis. In this regard, the present research, along with other studies, seeks to play a significant role in providing guidance for efficient decision making. Emphasizing the importance of understanding key aspects, such as Energy Payback Period (EPBT) and carbon emissions, and adapting them to the various regional contexts, the present research, together with other studies, seeks to play a significant role in providing guidance for efficient decision making.

5 Conclusions

- The qualitative assessment showed that the EPBT concerning the recycling of solar panels is often 2 to 4 months. An important observation in this regard is that regardless of the type of installation and energy consumption (in the cases analyzed), the EPBT remains constant and follows the same trend; however, the environmental footprint emitted in each case is directly proportional to the energy consumption of the case evaluated.
- Regarding the high energy consumption scenario, it is crucial to approach the results obtained with careful consideration. Although it is possible to achieve a rapid energy payback, which is evidenced by the remarkable EPBT of 0.25 years obtained in the analysis, it should be considered that this figure entails a considerable exchange in CO_2 emissions, obtaining significantly higher values with respect to the rest of the cases, totaling 4.78E+04 tCO_2 eq.
- It would be beneficial to include an in-depth explanation and quantification of the CO_2 emissions resulting from the energy consumed during the manufacturing process of PV panels. This analysis can further elucidate the carbon footprint associated with solar energy production and provide insights into potential mitigation strategies.
- Further investigation into the long-term performance and degradation of PV panels is essential. This includes examining factors such as material aging, module efficiency decline over time, and the impacts of installation conditions on panel durability. Such studies are crucial for accurately projecting the operational lifespan and energy yield of PV systems under real-world conditions.

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Conflicts of interest

The authors declare that there are no conflicts of interest to disclose. Furthermore, the authors confirm the following:

Data control:

- Authors assert that they have full control of all primary data collected during the research process.
- Authors agree to allow the journal to review their data upon request.

Data availability statement

This article has no associated data generated and/or analyzed. As such, there are no datasets to be deposited in a data repository.

Author contribution statement

- Conceptualization, Marco Yovera and Carlos Paragua.
- Methodology, Carlos Paragua.
- Validation, Marco Yovera, Carlos Paragua, and Melecio Paragua.
- Formal Analysis, Carlos Paragua.
- Investigation, Marco Yovera.
- Resources, Marco Yovera.
- Writing – Original Draft Preparation, Marco Yovera.
- Writing – Review & Editing, Marco Yovera, Carlos Paragua.
- Visualization, Melecio Paragua.
- Supervision, Carlos Paragua.
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