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THE IMPORTANCE OF STRUCTURE ON THE RECYCLABILITY OF SOLAR PANELS: DESIGNING LESS WASTE GENERATING PHOTOVOLTAIC PANELS (LWGPVP)

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Abstract:

Purpose: *The objective of this study is to propose a solution to reduce the wastes caused by the degradation of the end-of-life photovoltaic panels.* ***Design:*** *We conducted a scientific project in which we presented our design model as a solution for a less-waste generating PV panel. We focused on the external form of the rigid solar panels. Then, we evaluated our proposition with the conventional design economically and ecologically.* ***Methodology:*** *this research uses the quantitative method to estimate the expenditure requirements of the recycling cycle of our proposed model. It relies on the qualitative method to analyze both the conventional and sustainable cycles.* ***Approach:*** *it uses the comparative approach to compare between our proposed sustainable design and the conventional photovoltaic panel model in terms of design and the recycling phases.* ***Findings:*** *Our results show that the design features of foldability, removability and flexibility of our proposed model reduced the expenditures on natural and human resources and equipment to 38.75% .* ***Originality of the research:*** *This scientific contribution shows the significance of the external design of the panels in cutting recycling expenses. Less wastes generating PV panel is a promising solution to manufacture recyclable panels, economically efficient with less environmental footprint.*

***Keywords*:**

End-of-life Photovoltaic Panels; Recycling; Less waste generating solar panels; Sustainable design; Innovation

1. Introduction

The sun is the source of all creation on earth. It nurtured all forms of life including animals and plants on the primitive earth. By the coming of the human civilization, it constituted a source of divinity for the prehistoric man. Nowadays, we are exploiting its energy to operate and move our engines and devices. Historically, the first photovoltaic cell was invented by the French physicist Edmond Becquerel (1820-1891). He conducted experiments through which he discovered the photovoltaic effect in 1839. Later, several physicists and engineers like Willoughby Smith (1828 -1891) and Charles Fritts (1850 -1903) contributed with their discoveries to the elaboration of the early model of solar cells based on Selenium (Starowicz, Rusanowska and Zieliński, 2023: 171). In the present day, the solar panels are made from silicon. Further, a variety of photovoltaic panels are fabricated worldwide with the use of advanced technologies. In 2022, the global market of solar energy panels achieved $153.74 billion with a potential rise of compound annual growth with 9.01% (San Global Research, 2023). For instance, in 2022, the monocrystalline and the polycrystalline panels have the biggest share with a manufacturing rate of 27.94% and 25.47%. Meanwhile, Thin-Film panels got the less rate with 4.18% (San Global Research, 2023). However, it is important to note that due to its flexible aspects and the low manufacturing costs, the Thin-Film technology is evolving and expanding around the world. Further, the overall cumulative PV panels installations in the world bounced in ten years (between 2013 and 2023) from 138.856 megawatts to 1.624.000 megawatts (Fernández, 2024). However, the growing number of the PV installations prompts a bothering rate of pollution caused by the solar panels' wastes. End-of-life PV panels are full of harmful metals to human health such as Cadmium and lead. For this, they need to be treated carefully. Several causes can lead to their deterioration such as the end of their life-cycle and external harsh conditions. The solar panels constitute a fundamental element in sustainable development in the recent years. Though we deploy them worldwide for economic and environmental reasons, their wastes constitute a challenging situation that needs to be seriously addressed. We intend throughout this research paper to deeply analyze this problem in order to propose solutions for the academia and the industries. This study aims to demonstrate the importance of the form and structure of the solar panel in reducing the economic and environmental requirements of their recycling processes. The present paper purposes to answer the following problematic: How can the structure of the rigid solar panel impact its recycling process in terms of expenses and natural resources?

As a step to answer the problematic, this study tests the following hypotheses:

- ✓ The current installed photovoltaic panels generate sustainable energy and wastes too.
- ✓ End-of-life PV panels engender toxic metals and solid wastes too.
- ✓ The growing number of manufactured PV panels constitute a challenging problem to waste management companies.
- ✓ Restructuring the external design form of the panels with durable features is a sustainable solution economically and environmentally.

Besides, this research paper uses the international rating systems (ISO 14000, Cradle to Cradle Certified (C2C), and the LEED) to substitute a chart of norms that will be applied onto our model. Likewise, it uses them to substitute the criteria through which we categorize products with sustainability. Further, it relies on a variety of recent technical papers such as Md Shahariar Chowdhury, et al., (2020) An Overview Of Solar Photovoltaic Panels' End-Of-Life Material Recycling, Katarzyna Klejnowska, et al., (2024), Recycling of end-of-life PV panels - a review of Technologies, and Sajan Preet & Stefan Thor Smith (2024) A Comprehensive Review on the Recycling Technology of Silicon Based Photovoltaic Solar Panels: Challenges and Future Outlook to deconstruct the panels' causing elements of toxic wastes and to determine the common phases of solar panels' raw-materials recovery followed by the recycling factories.

To answer the working problematic, we have conducted our scientific project based on both qualitative and quantitative approaches. The former is based on a technical description of our LWGPVP model analyzing its design features structurally. Then, we evaluated our proposed PV panel model and assessed its efficiency economically and environmentally using the quantitative approach.

2. Methods :

As a step to answer our working hypotheses and provide solutions for the problematic, we have divided our scientific research into four thematic steps as follows:

- Step 1: Pre-Design phase: structuring a chart for less waste generating solar panels
- Step 2: Design phase
- Step 3: Modeling phase (see Results)
- Step 4: The assessment of the panel model (see discussion)

2.1. Step 1:

In fact, the objective of step 1 is to implement the fundamental criteria through which we claim a PV panel sustainable. The following chart of sustainable standards serves as a founding road map for our experiment and panel designing. Theoretically, sustainability is a broad concept; it encompasses a huge number of disciplines and sciences including construction, architecture, chemistry, economy … etc. However, other researchers went further by involving digitalization in project management as an important element to insure its sustainability (Budić, Marinac, and Ristanović, 2025: 49). Likewise, sustainability became associated with both economic and social walfare of societies (Bauer, Mösle, and Schwarz, 2010: 10). For this, we have structured the basic criteria of sustainability for the PV panels to narrow our perspective and subject matter into the renewable energy industry. We relied on the international standards indexed by different international organizations. Moreover, we formulated a set of criteria for less waste generating PV panels based on those standards. Our investigation concludes that all the indexed standards of green design, such as ISO 14000, Cradle to Cradle Certified (C2C), and the LEED rating system have common criteria of certification. They rate the degree of sustainability of any product based on the cycles of its production and post-manufacturing, toxicity of the used materials along the cycles, the consumption of the natural resources (water and primary materials), costs, air quality, social considerations, innovation and education too (ISO 14000, 2024; C2C, 2024; and USGBC, 2024). We ended into the following table.

Table 01: Less Wastes Generating Photovoltaic Panels' (LWGPVP) Standards Chart Life-cycle

Life-cycle			
Pre-production	**Manufacturing**	**Post-production**	
Sustainable design standards Modular design of the photovoltaic panels Circularity Innovative solar panels	Sustainable design Repurposing Reduce the development and production time Computer generated models Less transportation charges Less primary resources costs Healthy work conditions	New PV panels Longevity design Responsible end-of-life panels reuse Economic value Continuous cycle of assessment	Economic
Sustainable principles Eco-friendly designed PV panels Circularity	Reduce the development and production time Less toxic emissions of transportation and manufacturing machines Less natural resources consumption (water, primary resources …etc) Clean and healthy work environment	Less CO2 emissions Indoor environmental quality Outdoors environmental quality responsible wastes management Sustainable sourcing of materials Less environmental impact	Environmental

Source: Compiled by the author based on ISO 14000, Cradle to Cradle Certified (C2C), and the LEED rating system (ISO 14000, 2024; C2C, 2024; and USGBC, 2024)

2.2. Step 2:

In the design phase, we relied on the criteria mentioned in Step 1 as guidelines through which we design our model. The criteria are divided into economic and environmental elements involving several sustainable norms substituted from ISO 14000, Cradle to Cradle Certified (C2C) and the LEED rating system. Our model's design process comprises different steps including:

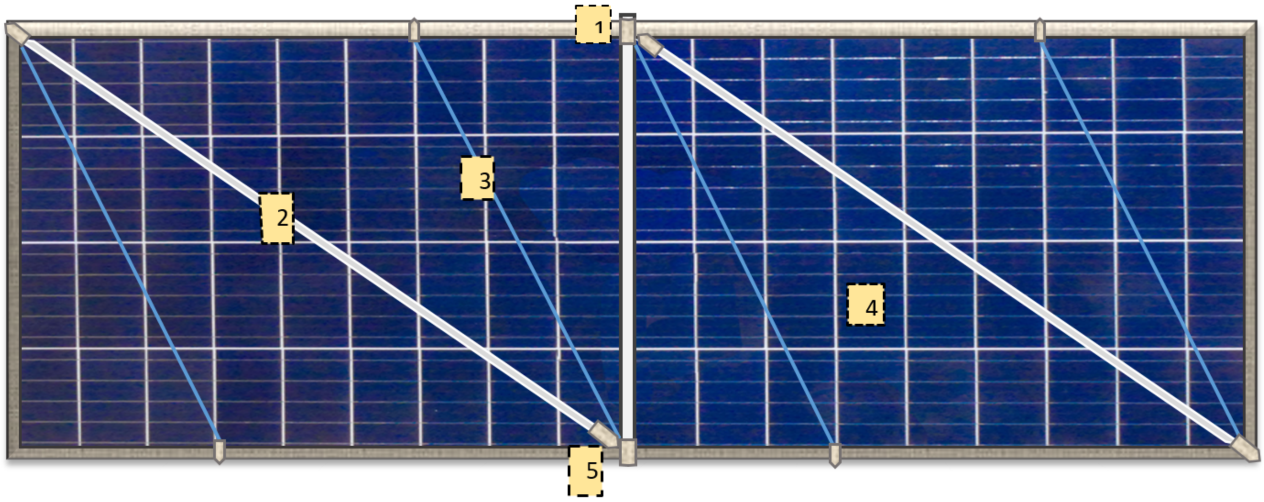
- Identifying model structural specifications and requirements
- Designing the model based on identified needs
- Model development and implementation based on our chart (see Table 01)
- Model study
- Model designing
- Revising the model

The following section demonstrates our proposed model of a less-waste generating PV panel.

3. Results :

Our research and conception ended into the design below. We designed our model based on our LWGPVP standards chart. Likewise, our proposed model is designed with geometric features. It is composed of an exterior aluminum frame that envelopes the parts of the panel. The frame is flexible as it can be folded by the two joints into two big parts (see figure 01, part 01). Further, both big parts are foldable too into two parts with triangular shape (see figure 01, part 02). The latter comprise two removable PV triangular parts per each. However, unlike the other previous parts, they are not foldable but removable.

Figure 01: The Proposed Less Wastes Generating Photovoltaic Panels' (LWGPVP) Model



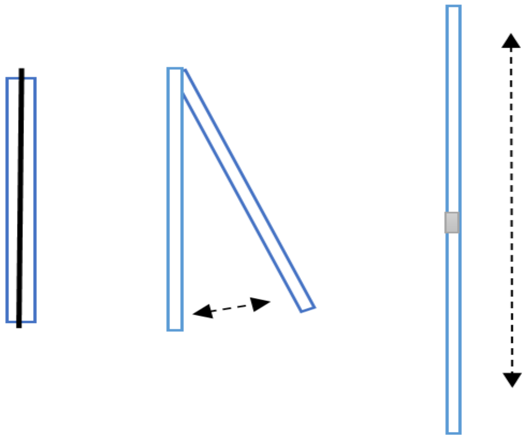
Source: The proposed LWGPVP model is designed by the author

The present PV panel design is based on three main aspects which are foldability, flexibility and removability. We designed the model relying on the three features to facilitate the recyclability of the rigid panel.

Firstly, foldability ensures the transportation of bigger amounts of the panels because they will occupy minimal space inside the tracks compared to non-foldable ones. This ensures the loading of more panels inside the track and reduces the number of shuttles and oil consumption as well.

Consequently, the transportation of the panels requires less expenses and reduces its environmental footprint as well.

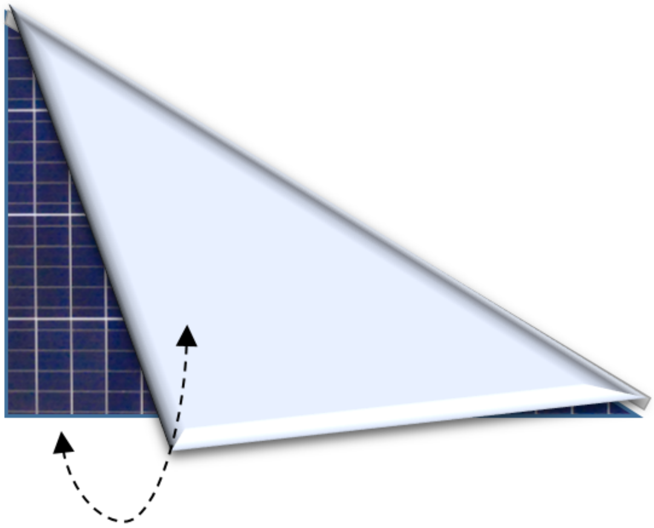
Figure 02: The Foldability Feature of the LWGPVP Model



Source: The proposed LWGPVP model is designed by the author

Secondly, the proposed model is designed to facilitate the removal of the damaged parts of the panel and replace them with new ones. By detaching parts with hot-spots, cracks, or visual defects like snail trails, the user can preserve his panel and maintain it without throwing it or transporting it into recycling factories.

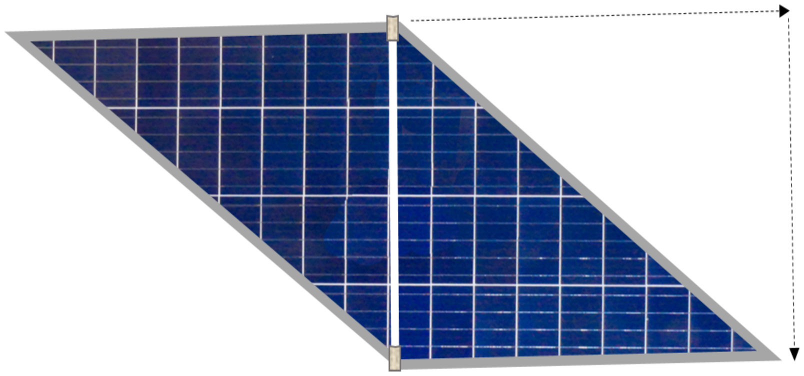
Figure 03: Removability Feature of the LWGPVP Model



Source: The proposed LWGPVP model is designed by the author

Thirdly, the proposed model of the recyclable solar panel is characterized with a flexible design. The latter enables the user to control the size of the panel by its irremovable but flexible parts. This aspect helps the user to adapt the size of the panel according to the required needs and uses by adding or detaching removable sub-parts.

Figure 04: Flexible Design of the LWGPVP Model



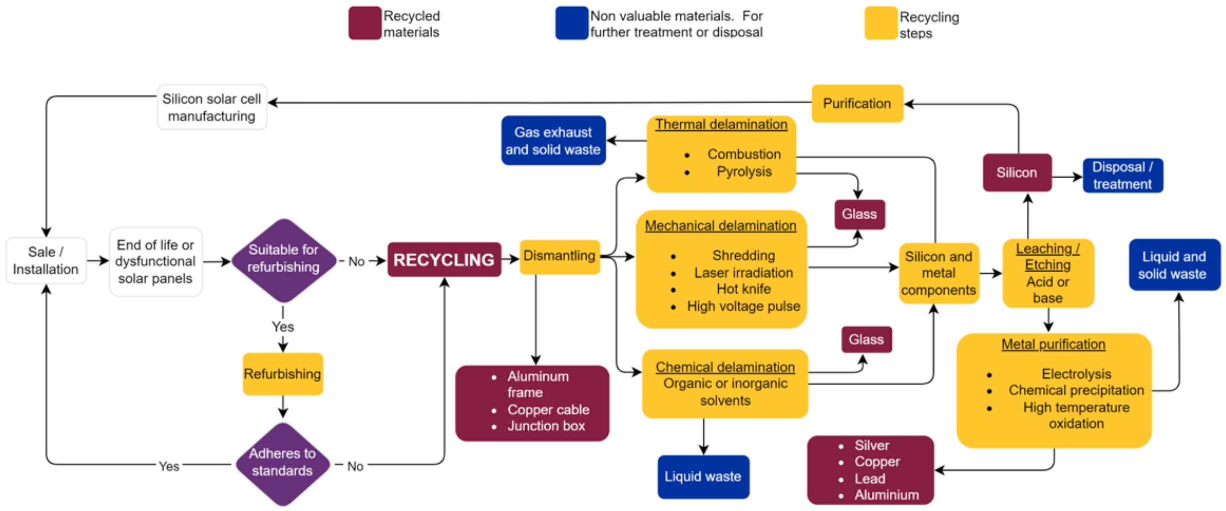
Source: The proposed LWGPVP model is designed by the author

The following section demonstrates the economic and environmental characteristics of the proposed model. It discusses its design as a solution for less wastes generating PV panel with less expenses.

4. Discussion

The present paper focuses on the wastes generated from the recycling process of the first generation solar panels. The latter comprise both polycrystalline and monocrystalline panels. However, the second-generation panels refers to Thin Film PV panels that include Amorphous, Cooper, Indium, Gallium and Selenium (CIGS/CIS), Cadmium Telluride (CdTe) and Copper Zinc Tin Sulfide (CZTS). The third generation panels refers to solar panels without P-N junction with less efficiency and life span. They include Organic cells (with organic semiconductors), and the hybrid Perovskite organic-inorganic cells (PSC) (Klejnowska, 2024: 02). According to the collected data, the recycling process of end-of-life photovoltaic panels (First Generation panels) comprises -but not limited to- three main methods, which are mechanical, thermal and chemical. The following diagram compels the three methods, phases and features of the recycling process of a PV panel.

Figure 05: Phases and Methods of the Recycling Process of PV Panels



Source: (Ganesan, 2024)

In fact, the used delamination method affects the costs of the recycling process. For instance, the mechanical method includes removing alumina frames using automatic crushers and the removal of the junction box and cables. It includes the separation of materials such as the silicon wafers, and it requires no expensive equipment. Moreover, the thermal method exposes the panels to pyrolysis at a temperature of 300° C to 650°C. The exposure of the panels to such high temperatures leads to the destruction of the adhesives and, thus, to the separation of materials such as glass. However, experts view that despite of the effectiveness of this method, its requirement of high temperatures leads into much energy consumption and to the generation of toxins (Ganesan, 2024).

Besides, the chemical method relies on solvents to separate parts of the solar panel. This process is effective to extract metals such as silver from the panel through chemical treatments. The latter undergo no damages over both the solar cells and the glass too. However, the acids are expensive and require time to be effective on adhesives. This process uses different regents -most of them are expensive- to disentangle the EVA layer from the solar panel. The acids can be organic or inorganic and can affect the PV cells whether by damaging them or recovering them. Likewise, the nitric acid is an operational solution to separate the EVA from the module; however, it generates important amounts of toxins like NO_2. Nevertheless, keeping the EVA in KOH-ethanol for 3 hours at a temperature of 200° C causes the recovery of 100% of the panel's cells with less environmental impact (Preet and Smith, 2024: 13).

Besides, the recycling of a rigid PV panel requires both financial and natural resources. Likewise, its process relies on equipment and acids that would emit wastes and toxic gases too. According to recent statistics, the recycling of PV panels costs \$10 to \$20 for a less than 100 watts panel and \$20 to \$30 for a medium panel of 100 to 250 watts. Moreover, the recycling may cost \$30 to \$40 watts for a 250 watts solar panel (The Solar Recycling Company, 2024). Further, other factors affecting solar panels recycling costs are transportation. Because of their large size and rigid from, the transportation of big quantities of solar panels (monocrystalline and polycrystalline) requires higher expenses compared to Thin-Film technology panels. The panels' large sizes entail additional logistical supplies such as tracks and fuel expenses. Further, this requires additional labor, thus, considering their wages too.

Our study proposes a sustainable design for rigid solar panels. Its geometric features makes the recycling process of the panel cost-effective with less environmental impacts. The following table demonstrates the economic and environmental advantages of our model compared to conventional rigid ground-mounted PV panels (CRGMPVP).

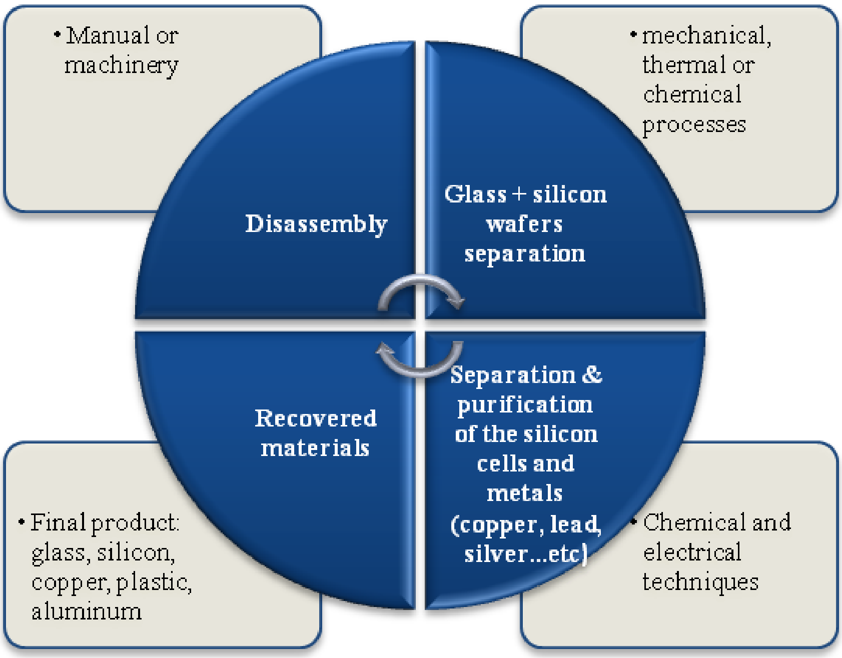
Table 02: The Economic and Environmental Impacts of the LWGPVP Model and the CRGMPVP

		Resources/ conditions	
Our LWGPVP Model	**CRGMPVP**		
- The removability feature of the LWGPVP reduces the amounts of EOL panels. - This leads to cutting chemicals' costs.	- The chemical process involves costs on the expensive regents (Chowdhury et al. 2020: 08). - Large quantities of EOL panels increase the chemicals delamination expenses.	Delamination costs	Economic
- The foldability feature of the LWGPVP reduces sizes of the EOL panels. This reduces shuttles and cuts transportation costs.	- Large amounts of EOL panels necessitate more logistical expenses on transportation.	Transportation costs	
- Less EOL panels to recycle reduces labor costs (wages). - Less junction boxes removal reduces labor costs too.	- The large amounts of EOL panels need more labor in mechanical, thermal or chemical processes. - EOL removal of junction boxes and frames needs more labor.	Labor	
- The removability feature leads to less EOL panels. - Recycling only the damaged parts leads to less energy and water consumption.	- The large amounts of EOL panels entail more energy and water consumption for the machines and the recycling processes.	Energy and water costs	
- Reduced amounts of EOL panels lead to cuttings in equipment purchase and maintenance costs. - Recycling only the damaged parts of the PV panel. - Less usage of the expander machines (for the frames). - Less usage of the shearing machine.	- More EOL panels need more recycling equipment such as devitrifying machines, expander machines, and shearing machines.	Equipment costs	
- Reduced amounts of EOL panels require less delamination chemicals. This leads to less toxic emissions. - Reduced number of EOL panels decreases transportation rates, thus, less environmental impact. - Less CO2 emissions compared to CRGMPVP. - Minimizing wastes generated from recycling process.	- More chemicals for the delamination process emit more toxins (Preet and Smith, 2024: 13) . - The transportation of the big amounts of EOL panels increases 60% to 90% of the environmental impact (Ghahremani et al., 2024: 285).	Generated wastes	Environmental
- Less natural resources consumption (energy and water). - Less EOL panels production. - Less materials damages (compared to the CRGMPVP). - Less grinding due to the reduced energy consumption.	- Moderate natural resources consumption. - The recycling process (mainly mechanical) leads to less energy consumption compared to thermal process that relies on energy and high temperatures (Ganesan, 2024).	Natural resources consumption	
- Less dust - Less wastes from the recycled materials - Less heat generated from the equipment - More comfortable workplace for the labor force - Improved indoor air quality.	- The use of some machines require the installation of fans inside the refineries because they generate heat. - The fans entail more energy consumption and extra electricity costs.	Air quality	

Source: the data are compiled by the author based on the technical features of the proposed model and other sources (Preet and Smith, 2024: 13; Ganesan 2024; Ghahremani et al. 2024: 285, and Chowdhury et al. 2020: 08).

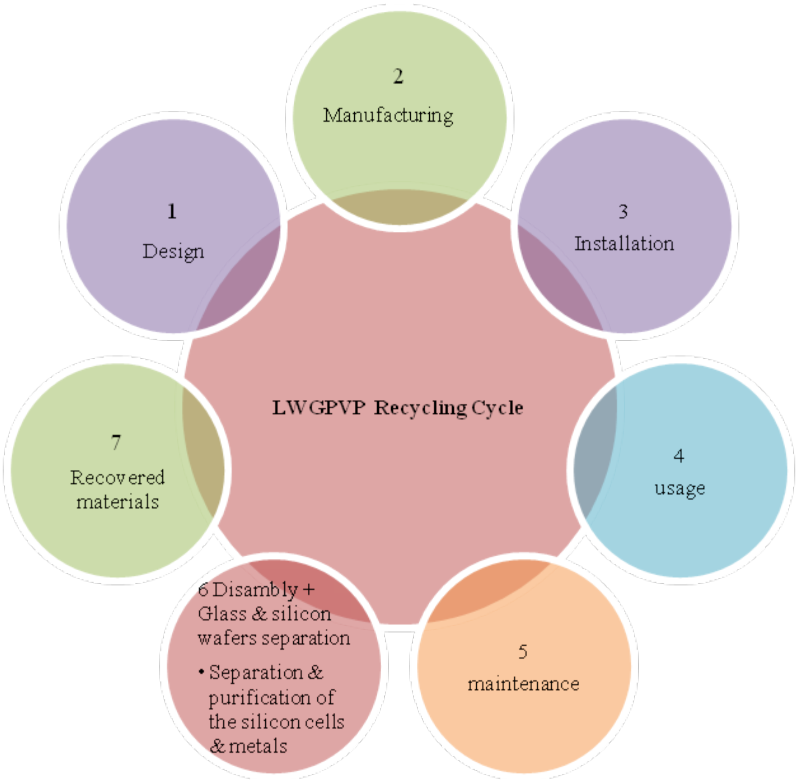
The diagrams below demonstrate the impact of the LWGPVP model on the recycling process of the solar panels. They show the different phases of both recycling cycles of a conventional solar panel and our proposed LWGPVP.

Figure 06: The Conventional Recycling Cycle of Conventional Solar Panels



Source: the data are compiled by the author from different sources (Ghahremani, A. et al,. 2024: 285; and Preet and Smith, 2024: 13).

Figure 07: The Recycling Cycle of our Proposed LWGPVP Model



Source: the data are compiled by the author

On the one hand, diagram 6 represents the main phases followed by almost all the recycling factories of solar panels. Our investigation reveals that the PV recycling industry relies mainly on four basic steps during their materials recovery which are:

1. The aluminum frame removal
2. The thermal, mechanical or chemical processes of glass and silicon separation
3. The EVA crushing and raw material separation
4. The collection of the recovered final materials which will be destined for reuse.

The recycling factories worldwide rely on this recovery cycle; however, they use different machines and chemicals depending on their budgets and available technologies.

On the other hand, diagram 7 represents the cycle phases of the recycling process of the proposed model of less wastes generating PV panels. The recycling of our LWGPVP model involves seven main phases which are:

1. Panel Design: This is a key step that determines the recyclability of the panel. It is based on the use of design standards that rely on innovation, modular design and sustainability. The final design must be economically efficient and with less environmental footprint. Our proposed PV model is foldable, removable and flexible. Its design enables the replacement of the damaged parts instead of buying a new panel, which reduces expenditures. Likewise, this decreases EOL panels' wastes in nature and the carbon emissions from their recycling process and transportation to the factory as well.

2. Panel Manufacturing: It involves the fabrication process of the modules from the early transformation of the raw materials into the final product.

3. Panel Installation: This phase refers to the installation process of the panels and the photovoltaic system.

4. Panel Use: The panels are generating electric power and can be re-sized according to the user's needs.

5. Maintenance: The user can detach the damaged parts and sub-parts of the panel and replace them with new ones without throwing the whole panel.

6. Panel Raw Materials Recovery: This phase involves the steps of the conventional recovery cycle of PVP. Instead of recycling the whole panel, the factory recovers the materials from the damaged parts or sub-parts only. In this phase, the aluminum frame removal can be skipped; this reduces the natural resources and financial requirements compared to the conventional cycle.

7. Recovered materials for Reuse: the final raw materials are collected (glass, silicon, copper, plastic, aluminum...etc) for a second exploitation.

Moreover, the following table sums up our comparison between the expenditures requirements between the the conventional recycling process and our proposed LWGPVP model. It demonstrates that the design features of our proposed solar panel model reduce the costs of the recycling. Further, the flexibility, removability and foldability of the LWGPVP reduce the panels quantity, installation costs, less logistical costs and requirements and less human and natural resources.

Table 03: A Comparison of Expences Requirements between the Conventional and the Proposed LWGPVP Model

Requirements	Expenses Requirements for both Cycles	
	Conventional Recycling Cycle	LWGPVP Recycling Cycle
Panels requirements	More panels with different sizes are needed (more expenses).	- Controlling the size of the panel leads to reducing the costs of buying extra panels.
Installation	More panels require more installation costs.	- Replacing only the damaged parts of the panels leads to less installation costs: - Less frames costs - Less labor - Less space exploitation
Damaged panels	- Damages can be fixed according to their levels. - Remarkably damaged panels will be delivered for recycling factories or landfill. - Large amounts of EOL panels require transportation costs. - More logistics in case the panels are big-sized.	- The design of the proposed LWGPVP extends the life-cycle of the panels. - The extension of the life-cycles of the panels leads to: ✓ Less labor costs ✓ Less machines requirements ✓ Less water costs and needs ✓ Less energy costs and needs ✓ Less recovery chemicals costs ✓ Less transportation and oil costs

Source: The comparison is realized by the author based on the results of the study

Besides, the following table quantifies the results of our study based on the findings of the previous tables and diagrams. We compared the expenditures requirements of a damaged rigid polycrystalline photovoltaic panel with two different designs (conventional and our proposed LWGPVP). The results below are approximative . We estimated the costs requirements of each panel based on a scale form 0 to 10 (0: non existent, 5: overage, and 10: high). We divided the resources into three main types which are human resources, natural resources and equipment.

Table 04: Estimation of the Expenditures Requirements for both Recycling Cycles

CRC	90%
PRC	51.25%
CRP/PVP	38.75%

Source: The estimation is realized by the author based on the results of the study

Our estimation of the rate of the resources costs ended into the following results. The raw-materials recovery of the damaged solar panel through the conventional recycling cycle CRC requires 90% of the natural and human resources and equipment. However, the recycling of the same solar panel with our proposed design requires less resources costs compared to the conventional one with a rate of 51.25%. Furthermore, our study estimated that our PVP model reduces the costs of the recycling process CRP into 38.75% per panel. The cuts in the expenditures of the recycling processes occur due to the following two key solutions:

- ✓ The extension of the raw-materials recovery cycle from 4 main phases into 7 phases.
- ✓ The design features of the proposed LWGPVP model are based on foldability, removability and flexibility.

The proposed innovative solar panel design aligns with the international standards and the regulatory framework of the renewable energy recycling industry and with the safety protocols. This ensures the feasibility of the proposed model and its applicability worldwide.

Stakeholder considerations were integrated into our design concept to ensure its practical adoption. Our model responds to the needs and requirements of our key stakeholders from different levels (government agencies, public and private factories and recycling enterprises, environmental organizations). Our model tends to attract investors, realize minimal environmental impacts and meet the governmental institutions' regulations and international standards. Incorporating the given aspects will support our model's relevance to both economic, societal and environmental norms.

A concise assessment of implementation barriers reveals a number of practical constraints. The latter may possibly limit the deployment of out proposed innovative sustainable design of photovoltaic panels. The constraints involve investment challenges related to the growing demand on the conventional models of solar panels which led to the emergence of large numbers of factories using expensive equipment adopted to this type of panels. This requires time and efforts for the factories to change their equipment types and reduce their labor too to adopt the sustainable PV panels. Likewise, cultural factors such as limited awareness about the importance of purchasing the ecofriendly photovoltaic panels may constitute a challenge for the implementation of the present innovative project.

5. Conclusion:

Recent reports and statistics suggest that the global installed solar PV capacity exceeded 1177 GW in 2022 and reached 1.3 TW in 2023 suggesting the global growth in the PV industry to reach 27 % in 2031. Likewise, the installation of the solar panels saves 35 tons of CO2 each year contributing to the protection of the environment (Ukpanah, 2024). In addition, the solar panels are made from recyclable materials such as glass, copper, plastic and aluminum. This encourages the factories to invest in the recovery of the PV panels' raw-materials. However, the growing amounts of the installed solar panels will constitute a heavy burden and a big challenge for the recycling factories as they will require more recovery enterprises. In addition, this will heavily increase the demand on the natural resources for the mechanical, thermal and chemical processes such as water, energy and chemical solvents. For this, our research proposed Less Wastes Generating Photovoltaic Panel (LWGPVP) as a solution for this challenge by focusing on the structural design of the solar panel. Our solution is based on the refinement of the rigid PV panel with three features; these are foldability, removability and flexibility. Our study estimates that the recycling of the LWGPVP decreases the expenditures on the natural and human resources and equipment to 38.75% compared to a conventional solar panel due to our extension of the recycling cycle and phases and to the design features of our model.

The present scientific research presents design concepts instead of empirical results. Based on our filed investigation and estimations of huge amounts of end-of-life solar panels in the near future, we propose an innovative design of a sustainable solar panel. We evaluated its environmental impacts based on Less Wastes Generating Photovoltaic Panels' Standards Chart Life-cycle that we realized based on international standards of different organizations and adopted them to solar panels design. Our objective is to set sustainable design milestones of solar panels that will be used in the future to realize a prototype that will be registered for a patent.

Our study presented a solution for the challenges that the recycling factories will face due to the growing number of the installed solar panels. It opens the doors for further development of innovative solutions for the PV industry that intertwine economic welfare, technological advancement, environmental protection and social well-being on the international scale. This will ensure a sustainable future for the coming generations and the continuity of the achievements realized by humanity in different fields such as science, technology, economy, innovation and society.

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