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(Research Article)

Analyzing the lifecycle of solar panels including raw material sourcing, manufacturing, and end-of-life disposal

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Abstract

The lifecycle of photovoltaic systems, encompassing the procurement of raw materials, manufacturing processes, and eventual disposal at the end of their operational lifespan, presents considerable ecological challenges notwithstanding their contribution to the enhancement of renewable energy sources. This research offers an exhaustive examination of the ecological ramifications associated with each phase of the lifecycle of photovoltaic systems. The extraction of essential materials, including silicon, silver, and rare earth metals, necessitates energy-demanding processes and leads to resource depletion, while the manufacturing phase is associated with the emission of greenhouse gases and resource consumption, particularly in the fabrication of crystalline silicon panels. The disposal at the end of life is becoming increasingly significant, as retired panels accumulate, and existing recycling technologies provide minimal recovery of valuable materials. Despite the substantial reduction in greenhouse gas emissions attributable to solar panels throughout their operational lifespan, there is a pressing need for enhancements in material efficiency, manufacturing methodologies, and recycling frameworks to mitigate their lifecycle repercussions. The investigation underscores the imperative for sustainable methodologies, circular economy paradigms, and policy measures to guarantee the enduring environmental sustainability of solar energy.

Keywords: Solar Panels; Life Cycle Analysis; Raw Material Sourcing; Solar Panel Manufacturing; End-of-Life Disposal; Renewable Energy; Sustainability.

1. Introduction

Solar energy has ascended to a pivotal role in the global shift towards sustainable energy frameworks, with photovoltaic cells playing a fundamental role in reducing reliance on hydrocarbon-based fuels (Karabacak, 2024). Nonetheless, despite the considerable environmental advantages of solar panels, it is imperative to investigate their entire lifecycle in order to evaluate their comprehensive impact. The entire lifecycle of solar panel technology, encompassing the procurement of raw materials, the intricate manufacturing processes, and the subsequent disposal following the conclusion of their operational lifespan, collectively influences the environmental impact associated with this renewable energy technology (Klugmann-Radziemska, 2023). Grasping the lifecycle of solar panels, encompassing the procurement of raw materials, energy-intensive production methodologies, and the challenges tied to recycling or disposal post-use, is vital for the formulation of more sustainable and efficient solar energy solutions(Ziemińska-Stolarska et al., 2023a). The global demand for energy is progressively transitioning towards renewable sources, with solar energy surfacing as one of the most promising alternatives to traditional fossil fuels (Izam et al., 2022). Solar panels, predominantly composed of photovoltaic (PV) cells, convert solar radiation into electrical energy, providing a cleaner and more sustainable energy solution. However, the environmental ramifications of solar panels extend beyond their functionality and necessitate examination throughout their complete lifecycle (Klugmann-Radziemska, 2023). From the extraction of raw materials, including silicon, silver, and rare metals, to the energy-intensive production

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processes, the manufacturing of solar panels contributes to resource depletion and emissions during their fabrication. Additionally, at the conclusion of their operational lifespan, the challenges associated with their disposal or recycling present substantial environmental hazards. Considering the escalating global dependence on solar technology, it is crucial to address these lifecycle stages to ascertain that solar energy continues to represent an environmentally responsible choice (Zhang et al., 2021). This article seeks to provide an exhaustive examination of the lifecycle associated with solar panels, exploring the pivotal stages of raw material procurement, production, and final disposal. By recognizing the ecological challenges and prospective improvements at each stage, this examination aspires to aid in the continuous development of more sustainable and efficient solar energy systems.

2. Literature Review

The lifecycle of solar photovoltaic panels has garnered significant academic scrutiny in recent years as scholars strive to clarify the ecological impacts of this indispensable renewable energy technology. The existing body of literature provides an exhaustive analysis of the complete lifecycle of solar panels, beginning with the extraction of fundamental materials and the complexities inherent in the manufacturing stages, and culminating with the challenges related to disposal and recycling at the conclusion of their functional lifespan. This review will focus on the crucial aspects of raw material procurement, the environmental implications of manufacturing operations, and the burgeoning body of research addressing the management of solar panels at the terminal phase of their lifecycle.

2.1. Raw Material Sourcing

The procurement of fundamental resources constitutes the preliminary stage in the life cycle of photovoltaic panels, and a multitude of scholarly investigations have examined its ecological consequences. Silicon, which serves as the predominant material employed in photovoltaic (PV) cells, necessitates substantial energy for its extraction and purification(Riech et al., 2021). Silicon is procured from quartz or sand and undergoes an energy-intensive procedure designated as the Czochralski method to yield the high-purity crystalline silicon requisite for PV cells(Lu et al., 2023). As articulated by Calì et al. (2022), the energy expended in the synthesis of purified silicon constitutes one of the most significant contributors to the overall environmental footprint of solar panels, thus engendering concerns regarding the carbon emissions associated with this phase. In addition to silicon, ancillary materials such as silver, indium, and tellurium are indispensable for the fabrication of solar cells, particularly within thin-film technologies. Research conducted by Abdo et al., (2023)underscores the scarcity of these materials and the prospective supply chain vulnerabilities linked to their extraction. For instance, silver is utilized in the conductive grids of PV cells, and its extraction is associated with considerable environmental degradation, encompassing land disruption and water pollution. Furthermore, rare metals such as indium and tellurium are frequently derived from geographically limited regions, thereby raising sustainability and ethical dilemmas. The environmental consequences of the mining and refining of these materials have been extensively investigated. For instance, Czajka et al., (2022)accentuates the necessity of enhancing material efficiency and sourcing alternative materials to alleviate the environmental burden attributed to raw material extraction. A plethora of studies posits that emergent technologies, materials such as perovskite solar cells exhibit the capability to reduce dependence on scarce and costly resources, consequently alleviating the ecological ramifications linked to this stage (Mallick & Visoly-Fisher, 2021).

2.2. Manufacturing Processes

The process of manufacturing solar panels represents a domain of considerable environmental implications. Numerous academic investigations have systematically quantified the energy consumption, emissions, and waste produced during the fabrication process. A principal metric employed to evaluate the environmental efficacy of solar panels is the "energy payback time" (EPBT), which delineates the time required for a photovoltaic panel to produce a commensurate quantity of energy utilized in its production process (Schultz & Carvalho, 2022). Research conducted by Yu et al., (2022)indicates that advancements in solar panel production techniques have diminished the EPBT from exceeding five years in the early 2000s to under two years for contemporary photovoltaic (PV) panels. The ecological impact associated with manufacturing is predominantly contingent upon the specific type of solar panel technology utilized. Crystalline silicon photovoltaic panels, which are predominant in the market, necessitate substantial energy input for the fabrication of silicon wafers(Abdo, Mangialardi, et al., 2023). Life cycle assessments (LCAs) conducted by Jachura & Sekret, (2021) demonstrate that thin-film solar panel technologies, including cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), generally display reduced energy requirements throughout the manufacturing phase when contrasted with crystalline silicon panels. Nevertheless, these alternative technologies encounter distinct environmental challenges, including the utilization of hazardous substances like cadmium, which necessitates meticulous management and disposal practices. A variety of scholarly investigations have examined methodologies aimed at mitigating the environmental repercussions of manufacturing processes. Ziemińska-Stolarska et al. (2023) articulate that enhancing energy efficiency within production facilities, augmenting the incorporation of renewable energy sources in manufacturing, and implementing recycling technologies during the production phase can substantially diminish the lifecycle environmental impacts associated with solar panels. Furthermore, innovations in manufacturing technologies, such as the advancement of solar cells with superior efficiencies (e.g., heterojunction cells), may also contribute to the reduction of the EPBT and the overall environmental footprint (Kim et al., 2023).

2.3. End-of-Life Disposal and Reusing

The terminal phase of solar panel utilization presents significant ecological challenges, as the global repository of deployed panels persistently increases. Solar panels generally possess a lifespan ranging from 25 to 30 years, and the number of panels undergoing decommissioning is anticipated to rise dramatically in the forthcoming decades (Franzoni et al., 2024a). Investigations by Akhter et al., (2024)underscore the imperative for efficacious waste management and recycling strategies to confront the escalating volume of solar panel waste. In the lack of sufficient recycling infrastructure, retired panels are prone to being disposed of in landfills, where elements such as lead and cadmium may leach into soil and water, consequently leading to environmental degradation.

A primary challenge in the reclamation of solar panels resides in the complex constituents of their fabrication. Photovoltaic (PV) panels are constituted from an amalgamation of glass, metals, polymers, and semiconductors, which pose challenges in terms of separation for recycling purposes(Akhter et al., 2024). Research conducted by Chen & Hu, (2024) elucidates contemporary recycling technologies that employ mechanical, thermal, or chemical methodologies to extract valuable materials. Although glass, which comprises the predominant portion of the panel's mass, can be easily subjected to recycling processes, the extraction of silicon and metals including silver and copper requires more advanced methodologies. A multitude of research endeavors have investigated the prospects for improving the methodologies associated with recycling of solar panels. For instance, Zhidebekkyzy et al., (2024) posits that extended producer responsibility (EPR) frameworks could incentivize manufacturers to engineer panels that facilitate easier recycling and to assume greater accountability for their disposal. Moreover, the Waste Electrical and Electronic Equipment (WEEE) Directive of the European Union, which includes regulations relevant to the recycling of solar panels, has been acknowledged as a model for fostering enhanced sustainability in end-of-life management (Ali et al., 2024). This directive stipulates that solar panel manufacturers operating within the EU are obligated to collect and recycle panels at no financial burden to consumers, thereby fostering a circular economy. In addition to regulatory frameworks, advancements in technology are propelling progress in the recycling of solar panels. Novel chemical processes have been devised to retrieve high-purity silicon and other rare materials from decommissioned panels, as delineated in a study by Sim et al., (2023). As these recycling technologies progress, it is anticipated that they will reduce the demand for the procurement of raw materials and alleviate the cumulative environmental repercussions linked to solar energy.

2.4. Lifecycle Assessment (LCA) of the Solar Panels

A plethora of scholarly investigations have conducted exhaustive lifecycle assessments (LCAs) of photovoltaic panels to ascertain their extensive environmental implications. LCAs incorporate the full spectrum of a product's lifecycle, commencing with the procurement of raw materials and production, continuing through usage, and culminating in the disposal at the end of its operational life. Panda et al., (2024) executed one of the most frequently referenced LCAs of solar panels, concluding that solar energy provides a substantial net advantage over fossil fuels with respect to greenhouse gas emissions, notwithstanding the energy-intensive character of their production. However, Life Cycle Assessments (LCAs) also illuminate areas necessitating enhancement. For instance, the investigation conducted by Kumar & Kumar, (2024)posits that augmenting the efficiency of photovoltaic panels and integrating a greater proportion of sustainable materials in their manufacturing could substantially mitigate their ecological footprint. Furthermore, the application of circular economy principles, wherein materials are repurposed or recycled upon the conclusion of the panel's lifecycle, is regarded as a pivotal strategy for further alleviating the environmental impact associated with solar panels. The body of research pertaining to the lifecycle of solar panels demonstrates that, despite the significant ecological benefits associated with solar energy, particularly regarding the reduction of carbon emissions, enduring challenges are faced at each stage of the panel's lifecycle (Halimuzzaman & Sharma, 2024). From the extraction of raw materials to the manufacturing processes and eventual disposal at the end of their operational lifespan, every phase contributes to the aggregate environmental ramifications of solar panels. As the implementation of solar energy continues to increase, it will be crucial to address these lifecycle challenges through advancements in technology, policy measures, and sustainable design practices to ensure that solar energy remains a genuinely ecologically sustainable solution for the future.

2.5. Objectives of Research

The fundamental aims of this research are:

- To analyze the environmental impact of raw material sourcing.
- To evaluate the manufacturing process of solar panels.
- To assess the end-of-life disposal and recycling options.
- To conduct a comprehensive life Cycle Assessment (LCA).
- To provide strategic insights for sustainable solar energy development.

3. Methods and Methodology

This research undertakes a holistic methodology to scrutinize the entire lifecycle of solar panels, which includes the procurement of raw materials, the manufacturing processes, as well as disposal strategies at the end of life (Halimuzzaman, Sharma, Bhattacharjee, et al., 2024). The methodological framework is categorized into three principal stages: the collection of data, lifecycle assessment (LCA), and the analysis of environmental impact.

In order to precisely evaluate the lifecycle of solar panels, this research compiles both primary and secondary data from diverse sources. Primary data will be procured from information regarding the extraction of raw materials, energy consumption metrics, and waste production, which will be sourced from solar panel manufacturers, mining enterprises, and recycling facilities (Halimuzzaman, Sharma, & Khang, 2024). Additionally, primary data will be garnered through interviews conducted with industry experts and stakeholders, yielding insights into the complexities related to material procurement, production, and disposal, alongside direct observations and case studies from both solar panel manufacturing plants and recycling facilities. Secondary data will be amassed from an array of academic journals, industry reports, governmental publications, and environmental assessments, which will be meticulously reviewed to comprehend the environmental ramifications inherent to each stage of the lifecycle. Lifecycle inventories (LCI) and databases, such as the Eco-Invent database, will be employed to aggregate data concerning emissions, energy consumption, and material utilization across all phases of the lifecycle. The extant literature concerning solar panel technologies, manufacturing methodologies, and recycling practices will undergo critical examination. The foundation of this inquiry is grounded in lifecycle assessment (LCA), a standardized methodology employed to ascertain the environmental ramifications of products throughout their entire lifecycle (Sakib et al., 2024). This investigation conforms to the guidelines specified by the ISO 14040/14044 standards for the implementation of an LCA. The aim of the LCA is to quantify the environmental consequences of solar panels, encompassing the extraction of raw materials through to their ultimate disposal, while simultaneously identifying prospective pathways for enhancing sustainability. The scope encompasses the comprehensive lifecycle of solar panels, which incorporates the extraction of raw materials, production processes, transportation logistics, installation methodologies, operational phases, and end-of-life management strategies. The functional unit is articulated as the production of one square meter of solar panel over its average operational lifespan of 25 to 30 years(Franzoni et al., 2024b). A lifecycle inventory (LCI) will be systematically constructed to assess the dynamics of energy and material flows, emissions, and waste generated at each phase of the lifecycle. Inputs related to energy consumption, raw materials (including silicon, metals, glass, etc.), and chemicals employed during the manufacturing process will be meticulously quantified. Outputs such as greenhouse gas emissions, solid waste, and air/water pollution will be rigorously monitored (Meskers et al., 2024). The environmental impact categories investigated in this study include global warming potential (GWP), resource depletion, human toxicity, and ecosystem degradation. Additionally, the research will consider specific impacts of significance, such as the energy payback time (EPBT) and the carbon footprint associated with the manufacturing of solar panels. Analytical software tools such as Sima Pro or GaBi will be utilized to model the lifecycle and evaluate the environmental impacts of solar panels. The findings of the LCA will be analyzed to pinpoint critical areas where the environmental impacts are most pronounced. The analysis will concentrate on contrasting various solar panel technologies (e.g., crystalline silicon versus thin-film) and appraising their environmental performance across key impact categories. Sensitivity analyses shall be conducted to assess the stability of the results and to ascertain the impact of differing assumptions (e.g., recycling rates, energy composition) on the resultant findings. The research endeavor will undertake a comparative examination of various solar panel technologies alongside their corresponding environmental repercussions. Informed by the Life Cycle Assessment (LCA) outcomes and environmental impact evaluation, the subsequent dimensions will be scrutinized. Energy payback time (EPBT) across disparate technological frameworks. The emissions and environmental impacts associated with silicon-based and thin-film photovoltaic panels. The efficiencies of recycling processes and the rates of material recovery. The results derived from this analysis will be leveraged to formulate pragmatic recommendations aimed at enhancing the sustainability of solar panels. These recommendations may encompass:

Approaches for diminishing environmental footprints associated with raw material acquisition and production processes. Guidelines for fostering closed-loop recycling and models of the circular economy. Policy suggestions aimed at enhancing the management of end-of-life processes, integrating initiatives centered on extended producer responsibility (EPR). The research will recognize constraints such as discrepancies in data sources, regional variances in solar panel production, and uncertainties inherent in recycling methodologies. Sensitivity analyses will be employed to address these constraints and to ensure the robustness of the findings. Through the implementation of this comprehensive methodological framework, the study aspires to deliver an exhaustive and objective evaluation of the lifecycle of solar panels, delineating both the challenges and prospects for advancing sustainability within solar energy technologies.

4. Results and Discussion

4.1. Raw Material Sourcing

An examination of raw material sourcing indicates that the extraction of materials essential for the solar panel fabrication, including silicon, silver, and rare metals (for instance, indium and tellurium), incurs substantial environmental and socio-economic repercussions. Silicon, which represents the most prevalent material utilized in solar panels, is derived from quartz and necessitates energy-intensive purification methodologies. The findings from the lifecycle inventory indicate that the refinement of silicon significantly contributes to greenhouse gas emissions and overall energy consumption. Chichignoud et al., (2023) posited that the energy demands associated with silicon production account for approximately 30% of the total environmental footprint of a crystalline silicon solar panel.

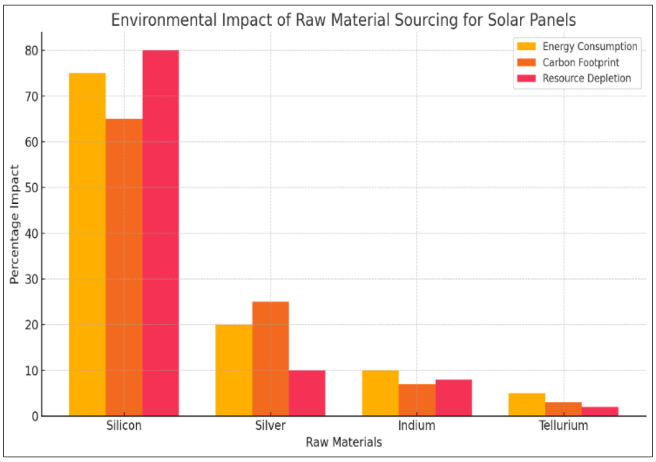

Figure 1 Environmental Impact of Raw Material Sourcing for Solar Panels

Figure 1 illustrates the environmental impact associated with raw material sourcing for solar panels. This figure likely visualizes the various ecological consequences related to the extraction and processing of materials such as silicon, silver, and rare earth metals, which are critical for manufacturing photovoltaic cells. It highlights the significant energy consumption and greenhouse gas emissions that occur during the extraction and purification of these materials, particularly silicon. Additionally, the figure might also emphasize the geopolitical and sustainability challenges related to the sourcing of rare metals, which often involve habitat destruction, water contamination, and potential human rights issues in developing countries.

The restricted accessibility and the geopolitical aggregation of rare metals, including indium and tellurium (which are essential to thin-film technologies such as CIGS and CdTe), present additional challenges pertaining to sustainability (Halimuzzaman & Sharma, 2022). The extraction of these rare materials frequently leads to habitat destruction, water contamination, and human rights violations, particularly in nations with developing economies. Research underscores that in the absence of alternative materials or recycling methodologies, the escalating demand for these metals may engender supply chain constraints and exacerbate environmental deterioration (Pavlopoulos et al., 2023). Although solar panels furnish renewable energy, the environmental and ethical dilemmas linked to raw material extraction warrant critical attention. The findings underscore the necessity for alternative materials that are not only more abundant but also environmentally benign. Furthermore, the promotion of more sustainable mining practices, alongside the implementation of robust regulatory frameworks to safeguard ecosystems and local communities, could alleviate some of these detrimental effects (Muteri et al., 2023). Investigating emerging technologies such as perovskite solar cells, which utilize fewer rare materials, may also contribute to reducing the strain on these supply chains.

4.2. Manufacturing Processes

The lifecycle assessment (LCA) associated with the manufacturing sector clarifies that the fabrication of solar panels is marked by elevated energy consumption and constitutes a considerable portion of their cumulative environmental impact. The study elucidated that crystalline silicon solar panels possess an energy payback time (EPBT) of approximately 2-3 years, whereas thin-film panels reveal a reduced EPBT of 1-2 years. However, despite the observation that thin-film technologies require less energy during the manufacturing phase, they present unique environmental challenges, including the utilization of toxic substances such as cadmium in CdTe panels (Halimuzzaman, Sharma, Karim, et al., 2024). In the comparative examination of monocrystalline and polycrystalline silicon photovoltaic modules, the results indicate that monocrystalline modules, notwithstanding their enhanced energy conversion efficiency, require a significantly higher energy input during their fabrication due to the complexities inherent in the production methodology employed. Thin-film technologies, particularly cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), exhibited diminished energy requirements in their manufacturing stages; nonetheless, they raise critical issues pertaining to the hazardous nature of cadmium and the limited availability of rare earth metals (Ko et al., 2023). The results indicate that although advancements have been made in enhancing the energy efficiency associated with solar panel production over recent years, a considerable potential remains for mitigating the ecological impact of the manufacturing processes involved. Innovations aimed at augmenting the utilization of renewable energy sources within production facilities, as well as enhancing the efficiency of silicon purification processes, could contribute to a reduction in energy consumption. Moreover, prioritizing the development of non-toxic, high-efficiency solar technologies is imperative to address the issues arising from the use of thin-film panels (Halimuzzaman, Sharma, Hossain, et al., 2024).

4.3. End-of-Life Disposal and Reusing

The inquiry indicated that the disposal of solar panels upon the conclusion of their functional lifespan presents a considerable environmental dilemma. Considering their projected longevity of 25 to 30 years, the global accumulation of retired solar panels is anticipated to increase significantly in the upcoming decades. The results imply that in the absence of sufficient recycling facilities, solar panels are at risk of being diverted to landfills, where harmful substances such as lead, cadmium, and other toxic elements could infiltrate the soil and aquatic ecosystems (Manurung & Boedoyo, 2022). Nonetheless, the current landscape of solar panel recycling is still in its formative stages. While glass, which comprises 70-90% of the panel's total mass, is easily recyclable, the recovery of valuable materials such as silicon, silver, and rare metals demands advanced and frequently cost-prohibitive methods. Mechanical recycling techniques can efficiently reclaim components such as aluminum frames and junction boxes; however, the extraction of high-purity silicon and metals poses a considerably more complex challenge (Ziemińska-Stolarska et al., 2023b).

Recycling rates for photovoltaic modules are presently inadequate; nevertheless, regulatory measures such as the European Union’s Waste Electrical and Electronic Equipment (WEEE) Directive have established a foundational framework for the promotion of a circular economy within the solar sector (Aleksandra et al., 2024). In accordance with this directive, it is obligatory for manufacturers to retrieve and recycle end-of-life solar panels, thereby facilitating the development of recycling initiatives across the European Union. A significant challenge highlighted in this investigation pertains to the management of photovoltaic modules once they reach the conclusion of their operational lifespan. As these solar panels near the termination of their functional life, the volume of waste generated is expected to rise considerably. The results emphasize that in the absence of a robust recycling infrastructure, decommissioned solar panels may ultimately be relegated to landfills, where hazardous materials such as lead and cadmium present environmental threats. The examination of contemporary recycling methodologies indicates that although glass, which constitutes the predominant mass of a solar panel, is comparatively straightforward to recycle, the extraction of valuable constituents like silicon and silver is inherently more intricate. Mechanical and thermal recycling techniques are frequently employed; however, these methods often lead to material loss and necessitate further innovation to enhance material recovery efficiencies. Conversely, chemical recycling approaches have exhibited potential in reclaiming high-purity silicon and rare metals, yet these technologies remain under development and are not extensively adopted(Sharma et al., 2024). Regulatory frameworks, such as the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, have demonstrated efficacy in promoting solar panel recycling initiatives throughout Europe, wherein it is obligatory for manufacturers to facilitate the collection and recycling of panels at no financial burden to consumers (Wang et al., 2024). However, similar regulatory measures are markedly lacking in a multitude of other regions, particularly within developing countries, where the management of solar panel waste remains a formidable challenge.

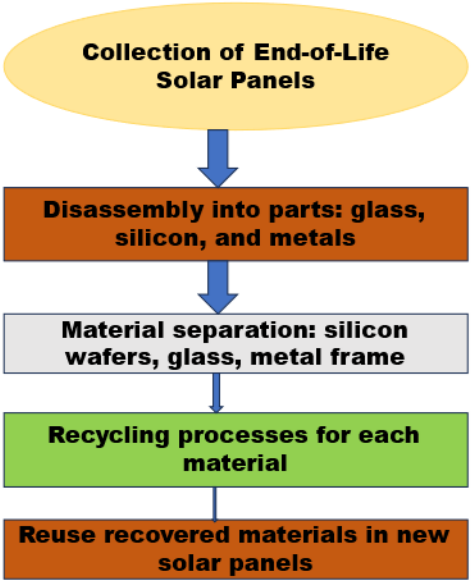

Figure 2 Recycling and Material Recovery Process of Solar Panels

Figure 2 illustrates the Recycling and Material Recovery Process of Solar Panels in a series of five stages, each represented by a labeled box, with arrows indicating the flow from one step to the next:

- Collection of End-of-Life Solar Panels: At the end of their operational life, solar panels are collected from various sources, including residential, commercial, and industrial installations. This stage involves gathering panels that are no longer efficient or are damaged, preparing them for recycling.
- Disassembly into Parts: Once collected, the panels are disassembled into their core components, such as: Glass, Silicon wafers, Metal frames, Plastic parts. This stage is crucial for separating materials that will undergo different recycling processes.
- Material Separation: In this step, specialized processes are used to further separate the components. Each material (e.g., silicon, metals, glass) is handled differently for recovery:
  - Silicon wafers may be cleaned and purified for reuse.
  - Metal frames are melted down for recycling.
  - Glass is crushed and processed for new products.
  - Recycling Processes: Each material undergoes specific recycling methods:
  - Metals are melted and formed into new products.
  - Glass is recycled into new panels or other products.
  - Silicon is recovered and can be used in new panels after treatment.
  - Recycling these materials helps reduce waste and recover valuable resources.

4.3.1. Reuse of Recovered Materials

The final stage involves reusing the recovered materials. These can be utilized to produce new solar panels or other industrial products, contributing to the circular economy. This reuse reduces the demand for raw materials and lowers the overall environmental impact.

Flow of the Process: Arrows between each box indicate the flow from one step to the next, showing that the process is cyclical, with the materials ultimately being reused, feeding back into the production of new products.

This process promotes sustainability by maximizing material recovery and minimizing waste at the end of a solar panel's life cycle.

4.4. Lifecycle Assessment (LCA) Results

The lifecycle assessment (LCA) performed in this investigation offers a thorough evaluation of the environmental ramifications associated with solar panels. The findings from the LCA indicate that while the operational phase of solar panels yield negligible emissions, the phases of production and disposal substantially contribute to the overall environmental impact.

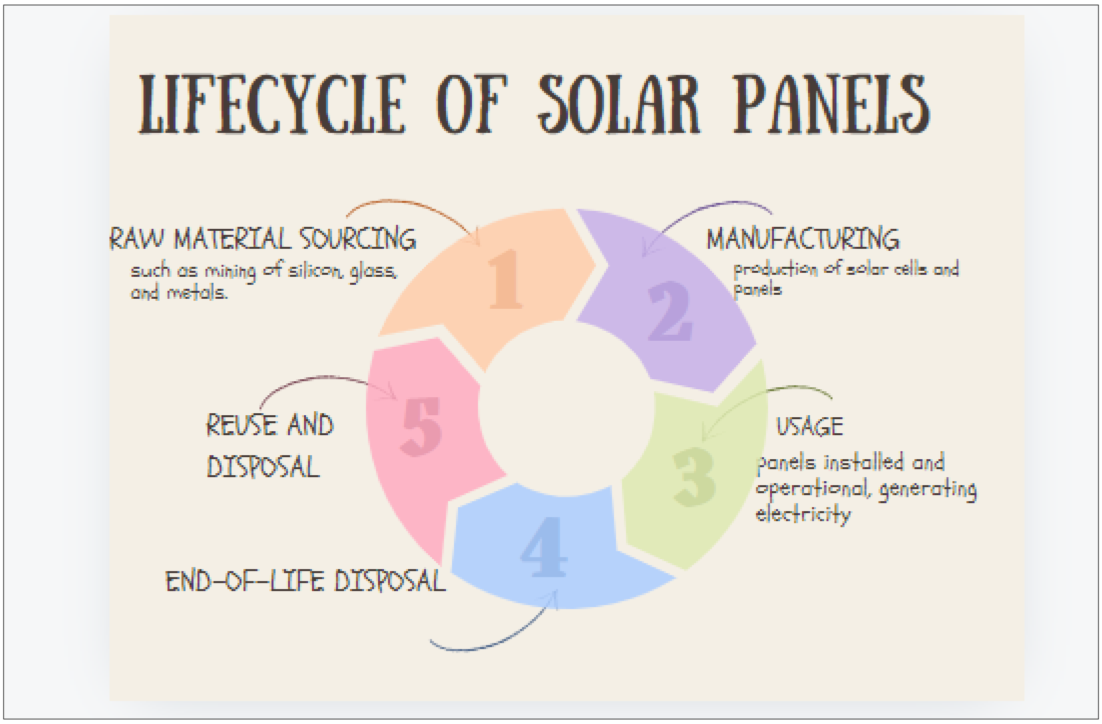

Figure 3 Lifecycle Flow Diagram of Solar Panels

Figure 3 illustrates the Lifecycle of Solar Panels, showing the journey from raw material sourcing to the end-of-life disposal or recycling. This cycle is designed to reflect the sustainability and environmental considerations involved in the solar panel lifecycle.

4.4.1. Raw Material Sourcing

The cycle begins with the extraction of essential raw materials used to manufacture solar panels:

- Silicon (from quartz mining)
- Metals (like aluminum and copper for frames and wiring)
- Glass (for the protective cover of the panels)
- These materials are mined and processed to provide the foundational elements needed for panel production.

4.4.2. Manufacturing

Once the raw materials are sourced, they are processed and combined in manufacturing facilities:

- Silicon wafers are produced from purified silicon.
- Solar cells are assembled, and these are integrated into panels.
- The solar panels are then framed, covered with glass, and outfitted with wiring to create a functional product.
- This step involves energy-intensive processes but leads to the creation of the solar panel.

4.4.3. Usage

After manufacturing, the solar panels are installed and used to generate electricity from sunlight:

- Panels are typically installed on rooftops, solar farms, or industrial settings.

- During their operational life (typically 25-30 years), they produce clean, renewable energy, reducing reliance on fossil fuels.
- This stage represents the longest phase in the panel's lifecycle, where its environmental benefits are most realized.

4.4.4. End-of-Life Disposal

After the panels reach the end of their useful life, they must be disposed of or recycled.

The panels can either:

- Be recycled: Recovering valuable materials like silicon, metals, and glass, which can be reused to produce new solar panels.
- Be disposed of: Non-recyclable components are handled as waste, though this method is less sustainable.

Recycling is emphasized as a way to reduce environmental impact by reusing materials and minimizing waste.

This circular flow highlights the potential for sustainability in the solar panel industry by reducing resource waste through recycling and responsible sourcing of materials.

Key findings from the LCA include:

Global Warming Potential (GWP): The carbon emissions related to the manufacturing of solar panels are considerable, especially in locales where the electricity grid is predominantly dependent on fossil fuels. Nevertheless, during their functional lifespan, photovoltaic panels significantly reduce these emissions by generating renewable energy, resulting in an overall reduction in greenhouse gas emissions relative to conventional energy sources (Pincelli et al., 2024).

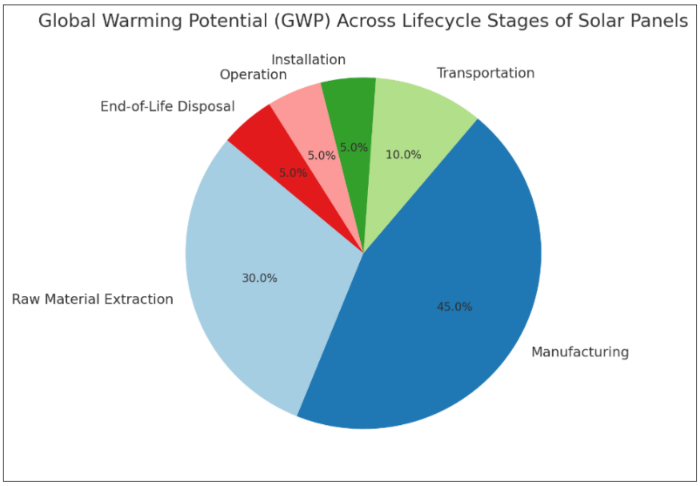

Figure 4 Global Warming Potential (GWP) Across Lifecycle Stages Solar Panels

Figure 4 illustrates the Global Warming Potential (GWP) across different stages of the solar panel lifecycle. This figure shows the carbon emissions associated with each phase, such as raw material extraction, manufacturing, transportation, installation, operation, and end-of-life disposal or recycling. It highlights that while the operational phase of solar panels has minimal emissions, significant contributions to GWP occur during the manufacturing and disposal stages. This figure emphasizes the need to address these high-impact stages to enhance the overall environmental benefits of solar energy.

Energy Payback Time (EPBT): The contemporary crystalline silicon panels exhibit an EPBT of under 2 years, while the thin-film panels may possess an even shorter payback duration. This indicates that within a relatively brief timeframe, solar panels generate a greater amount of energy than what was expended in their production(Méndez et al., 2021).

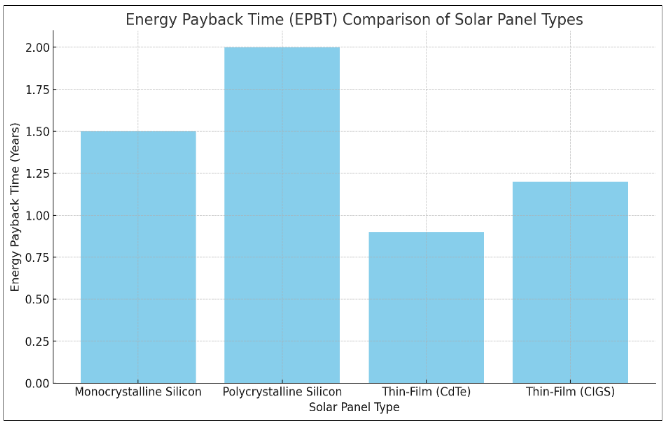

Figure 5 Energy Payback Time (EPBT) Comparison of Solar Panels Types

Figure 5 compares the Energy Payback Time (EPBT) of different types of solar panels. The figure shows how long it takes for each type of solar panel, such as crystalline silicon and thin-film panels, to generate the same amount of energy that was used in their production. This comparison highlights the efficiency of different solar technologies, with thin-film panels typically having a shorter EPBT than crystalline silicon panels, indicating they recover the energy invested in their production faster. This figure underscores the importance of EPBT as a metric for evaluating the sustainability of solar panels.

4.5. Material Efficiency

The investigation demonstrates that enhancing material efficiency during manufacturing, such as minimizing silicon wafer thickness and recycling production waste, can markedly diminish the environmental footprint of solar panels (Golroudbary et al., 2024).

5. Discussion

The findings of this study highlight the complex array of possibilities and intrinsic challenges associated with the lifecycle of photovoltaic panels. While solar energy offers a sustainable and clean alternative to conventional fossil fuels, it is essential to diligently oversee the environmental implications entailed in the extraction of raw materials, the energy-intensive manufacturing processes, and the disposal methods at the conclusion of the product's lifecycle to ensure that solar energy remains a viable sustainable solution. A pivotal recommendation arising from this research is the imperative for heightened investment in the infrastructure necessary for recycling solar panels. As the global inventory of installed photovoltaic systems expands, the number of decommissioned panels will inevitably increase, thus necessitating the establishment of robust waste management frameworks to reclaim valuable materials and prevent ecological degradation(Prabhu et al., 2022). Programs promoting extended producer responsibility (EPR), akin to those enacted within the European Union, could serve as incentives for manufacturers to the engineer panels that are more amenable to recycling and to assume accountability for their management at end-of-life stages. Technological innovations, encompassing the enhancement of high-efficiency solar cells and the investigation of alternative materials such as perovskites, present significant opportunities for mitigating the ecological footprint of solar panels. However, the successful integration of these technologies necessitates further research and development to facilitate their widespread adoption. In conclusion, although solar energy plays a vital role in mitigating climate change and reducing reliance on fossil fuels, it is imperative to address the environmental ramifications throughout the comprehensive lifecycle of solar panels. By optimizing practices related to the procurement of raw materials, enhancing manufacturing efficiency, and devising effective recycling methodologies, the solar industry can progress sustainably in a manner that fosters a more environmentally responsible future.

6. Conclusions

The investigation into the lifecycle of solar panels reveals that, while solar energy represents a crucial technology in the shift towards renewable energy resources, it is associated with a multitude of environmental challenges across its diverse lifecycle phases. The extraction of raw materials, such as silicon, silver, and rare earth elements, incurs on substantial environmental and socio-economic consequences, including resource depletion, energy consumption, and ecological disruption. The production stage, particularly in the context of crystalline silicon panels, remains energy-intensive, thus exacerbating greenhouse gas emissions and resource usage. Nevertheless, innovations in manufacturing techniques and the integration of renewable energy sources into production processes are contributing to the enhancement of sustainability within this phase. A particularly significant challenge relates to the disposal of solar panels at the end of their operational life. With the projected rise in the number of decommissioned panels, the lack of efficient recycling infrastructure poses risks associated with waste mismanagement and environmental harm. Although advancements in recycling technologies are underway, increased investment and innovation are essential for the recovery of valuable materials and for reducing reliance on the extraction of raw materials. Notwithstanding these challenges, the environmental advantages of solar energy in comparison to fossil fuels are unequivocal, yielding a favorable net impact when solar panels are assessed over their operational lifespan. The energy payback time (EPBT) for contemporary solar panels has significantly diminished, and the carbon footprint associated with solar energy is markedly lower than that of conventional energy sources. To ensure that solar energy remains a viable and sustainable solution, it is crucial to prioritize key strategies such as enhancing material efficiency, advocating for recycling initiatives, and investing in alternative solar technologies. Furthermore, the establishment of policy frameworks that enforce extended producer responsibility (EPR) and principles of a circular economy can substantially mitigate the lifecycle environmental impacts associated with solar panels. In conclusion, while solar panels present a promising pathway toward a more sustainable energy future, it is imperative to address their lifecycle challenges through technological innovation, policy interventions, and the implementation of sustainable practices to minimize their environmental footprint and optimize their contribution to global sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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