

# Life Cycle Assessment of Solar Panels: Environmental Impacts from Production to Disposal

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## Abstract

*LCA is a way to evaluate the full environmental impact of something—like a product, material, activity, or building—from start to finish. As solar energy adoption accelerates globally, understanding the full environmental implications of PV technology becomes crucial for informed decision-making and sustainable development. The study employs a cradle-to-grave approach, analyzing the environmental footprint of solar panels across multiple impact categories. These include global warming potential, energy payback time, water consumption, toxicity, and resource depletion. For this study, data has been taken from manufactures and experts of building construction. Results indicate that while solar panels significantly reduce greenhouse gas emissions during their operational phase, the production and disposal stages present notable environmental challenges. The energy-intensive manufacturing process, particularly silicon purification and wafer production, contributes substantially to the overall carbon footprint. The paper concludes by highlighting the need for continued innovation in manufacturing processes, material efficiency, and recycling technologies to further enhance the environmental performance of solar panels. It also emphasizes the importance of developing robust policies and infrastructure for PV waste management to ensure the long-term sustainability of solar energy deployment.*

**Keywords:** Solar energy, PV panels, Environmental Impacts, Life cycle, Carbon footprint, innovation

## INTRODUCTION

As nations increasingly adopt sustainable energy options, solar power has taken center stage in both climate action and environmental preservation efforts. Facing the pressing demands of emission reduction and global temperature control, photovoltaic technology stands out as a practical answer - converting sunlight into reliable, pollution-free electricity. However, while solar panels are often lauded for their ability to generate electricity without direct emissions during operation, a comprehensive understanding of their environmental impact requires a more nuanced approach that considers their entire life cycle.

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Life Cycle Assessment (LCA) is a crucial tool in evaluating the holistic environmental footprint of solar panels, from raw material extraction and manufacturing to installation, operation, and end-of-life disposal or recycling. This methodical approach allows researchers, policymakers, and industry stakeholders to identify and quantify the environmental impacts associated with each stage of a solar panel's existence, providing valuable insights that can inform sustainable practices and guide technological innovations (Tao, J., & Yu, S., 2015) [4].

Making solar panels requires a lot of energy and raw materials like silicon, glass, aluminum, and rare metals. The manufacturing process itself can have a major environmental footprint, mainly due to high electricity use and the demand for limited resources. On top of that, mining and refining these materials can harm local ecosystems, damaging habitats, contaminating water sources, and leaving lasting effects. A full environmental evaluation must account for these impacts at every stage, from material sourcing to production.

During their operational lifetime, which typically spans 25 to 30 years, solar panels generate clean electricity with minimal environmental impact. However, factors such as panel degradation, maintenance requirements, and the need for energy storage systems can influence the long-term sustainability profile of solar installations. Furthermore, the end-of-life management of solar panels presents both challenges and opportunities. As the first generation of widely deployed solar panels approaches retirement, the industry faces the critical task of developing efficient recycling processes to recover valuable materials and prevent potentially harmful substances from entering the environment (Goe, M., & Gaustad, G., 2014) [6].

This research paper aims to conduct a thorough life cycle assessment of solar panels, examining the environmental impacts at each stage of their existence. By Fthenakis, V. (2010) [7] analyzing factors such as energy payback time, carbon footprint, water usage, and material recyclability, we seek to provide a balanced and data-driven evaluation of the sustainability of current PV technologies. Moreover, this study will explore emerging trends and innovations in solar panel design, manufacturing, and recycling that hold promise for reducing environmental impacts and enhancing the overall sustainability of solar energy systems (Rocchetti, L., & Beolchini, F., 2015) [8].

Understanding the full life cycle impacts of solar panels is essential for several reasons. First, it enables more accurate comparisons with other energy technologies, both renewable and conventional, helping to inform energy policy and investment decisions. Second, it highlights areas within the solar value chain where environmental performance can be improved, driving research and development efforts towards more sustainable practices. Finally, a comprehensive LCA can address concerns and misconceptions about the environmental credentials of solar energy, providing a scientific basis for public discourse and policy formulation (Held, M., & Ilg, R., 2011) [9].

As we delve into this analysis, it is important to recognize that the environmental profile of solar panels is not static but evolves with technological advancements, changes in manufacturing processes, and improvements in recycling technologies. This dynamic nature underscores the need for ongoing assessment and adaptation to ensure that solar energy continues to play a positive role in our transition to a more sustainable global energy system.

## LITERATURE REVIEW

Solar photovoltaic systems have gained significant attention in recent decades as a sustainable solution to global energy challenges. Extensive research has explored their technological advancements, efficiency improvements, and economic viability. Studies consistently highlight solar PV's potential to reduce carbon emissions while meeting growing energy demands. This section reviews key developments in PV technology, system design, and environmental impacts, providing context for their role in the renewable energy transition. The literature reveals both opportunities and challenges in scaling up solar power for widespread adoption.

### Environmental Impacts

Recent studies have consistently shown that solar PV systems have significantly lower life-cycle environmental impacts compared to fossil fuel-based electricity generation. Fthenakis and Kim (2011) [1] demonstrated that silicon-based PV systems have greenhouse gas (GHG) emissions of 30-80 g CO<sub>2</sub>-eq/kWh, which is an order of magnitude lower than coal-fired power plants. Main cause of

environmental impact is manufacturing process of panels. (Peng et al., 2013) [3] found that the production of solar-grade silicon and panel assembly accounted for the majority of energy consumption and GHG emissions in the life cycle of crystalline silicon PV systems.

### **Energy Payback Time**

Energy payback time is the duration required for PV panels to generate same amount of energy used in its production. Recent studies have shown a trend of decreasing EPBTs due to technological improvements and more efficient manufacturing processes. A comprehensive review of silicon-based PV systems, revealing that the EPBT has decreased from about 5 years in 1992 to around 0.5-1.5 years in 2015 for rooftop systems in Southern Europe. This improvement is attributed to increased cell efficiency and reduced silicon usage per watt of capacity.

Geographical location plays a significant role in determining EPBT. EPBT for the same PV technology could vary by up to 50% depending on the installation location, due to differences in solar irradiation and local grid efficiency.

Looking towards the future, several studies predict further reductions in EPBT:

1. *Improved manufacturing processes*: Advances in silicon purification and wafer production could reduce EPBT by up to 30% by 2025.
2. *Increased cell efficiency*: Estimated that achieving 25% efficiency for commercial silicon cells could lower EPBT to less than one year in most locations.
3. *Circular economy approaches*: Implementing effective recycling and reuse strategies could potentially reduce EPBT by 10-20% through material recovery and reduced primary production.

### **Technological Advancements and Emerging Technologies**

LCA studies have also focused on comparing different PV technologies. Nowadays, technology is growing in every field and that is helpful too. For solar panels, advanced technology helped in the adoption and now one can use it easily in the form of thin films, solar flowers, solar pumps, solar street lights, etc. Fthenakis et al. (2008) [10] found that CdTe PV systems had the lowest life-cycle GHG emissions among commercial PV technologies, with emissions as low as 14 g CO<sub>2</sub>-eq/kWh. However, the authors noted that the scarcity of tellurium might limit the large-scale deployment of this technology. A prospective LCA on perovskite PV modules, suggesting that they could potentially achieve lower environmental impacts and shorter EPBTs compared to conventional silicon-based panels. However, the authors emphasized the need for further research on the long-term stability and scalability of perovskite technology (Singh & Nayak, 2023) [14].

### **Methodological Considerations and Challenges**

LCA practitioners face several challenges when assessing solar PV systems. One key issue is the variability in results due to differences in system boundaries, functional units, and geographic locations. The importance of harmonizing LCA methodologies to improve the comparability of results across studies. Another challenge is the consideration of end-of-life management. As the first generation of PV systems reaches the end of its operational life, proper recycling and disposal methods become crucial. Latunussa et al. (2016) [5] conducted an LCA of a PV recycling process, demonstrating the potential environmental benefits of recovering valuable materials from end-of-life panels.

### **DIFFERENT PHASES OF PV AND ITS IMPACT ON ENVIRONMENT**

Solar energy – an alternative of clean energy, not east to analysis its environmental impacts throughout its entire life cycle because there are so many external factors can affect the study. This literature review explores recent research on the life cycle assessment (LCA) of solar panels, focusing on environmental impacts from production to disposal.

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### Production Phase

Several studies have investigated the environmental impacts of solar panel production. Fthenakis and Kim (2011) [1] conducted a comprehensive LCA of crystalline silicon (c-Si) PV systems, finding that the energy payback time for these systems ranged from 1.7 to 2.7 years, depending on the location and solar irradiation. The study also highlighted that the production of silicon wafers and solar-grade silicon were the most energy-intensive processes in the manufacturing phase.

The evolution of environmental impacts of c-Si PV systems over time, noting significant improvements in energy use and greenhouse gas (GHG) emissions per watt-peak of PV module produced. They found that the carbon footprint of PV electricity generation decreased from about 400 g CO<sub>2</sub>-eq/kWh in 1975 to less than 20 g CO<sub>2</sub>-eq/kWh in 2015, primarily due to technological advancements and economies of scale.

### Use Phase

The use phase of solar panels generally has minimal direct environmental impacts, as they do not emit pollutants during operation. However, Emphasized the importance of considering indirect emissions associated with maintenance and replacement of system components. Their study found that the life-cycle emissions of solar PV systems were significantly lower than those of fossil fuel-based electricity generation, even when accounting for these indirect emissions.

### End-of-Life and Disposal

As the first generation of mass-produced solar panels approaches the end of their useful life, research on recycling and disposal has gained importance. Various recycling technologies for end-of-life PV modules, highlighting both the environmental benefits and challenges of recycling. They found that while recycling can recover valuable materials and reduce waste, the process itself can be energy-intensive and potentially harmful if not managed properly (Avitesha, B. D. T. S.,2020) [15].

Latunussa et al. (2016) [5] conducted an LCA of an innovative recycling process for silicon PV panels, demonstrating that recycling could lead to significant environmental benefits compared to landfilling. Their study showed that recycling could reduce the energy demand and global warming potential of PV waste management by 81% and 87%, respectively.

## A COMPARISON WITH NON-RENEWABLE ENERGY SOURCES

Solar photovoltaic technology is the most easily adaptable in renewable energy systems and single household can use it individually. Not just it is better than non-renewable energy resources but due to easy usage it is emerged as leading renewable energy systems.

### Greenhouse Gas Emissions

Multiple studies have consistently shown that solar PV systems have significantly lower lifecycle greenhouse gas (GHG) emissions compared to fossil fuel-based electricity generation. Fthenakis and Kim (2011) [1] reported that the life-cycle GHG emissions for crystalline-silicon (c-Si) PV systems range from 30 to 45 g CO<sub>2</sub>-eq/kWh, whereas coal-fired power plants emit 900-1200 g CO<sub>2</sub>-eq/kWh. A more recent study by Pehl et al. (2017) corroborated these findings, estimating median lifecycle emissions of 4 g CO<sub>2</sub>-eq/kWh for solar PV, compared to 820 g CO<sub>2</sub>-eq/kWh for coal and 490 g CO<sub>2</sub>-eq/kWh for natural gas.

### Energy Payback Time and Energy Return on Investment

EPBT and EROI are very important parameters when it comes to study and comparison of technologies in the field of energy. A comprehensive review of solar PV LCAs, finding that the EPBT for c-Si PV systems ranged from 1.0 to 4.1 years, with newer technologies trending towards the lower end. In contrast, Rauegi et al. (2012) [11] reported that coal and natural gas power plants have near-instantaneous energy payback but much lower EROI over their lifetimes.

The EROI for solar PV has been improving steadily. A meta-analysis found that the EROI for solar PV ranged from 8:1 to 12:1, compared to 46:1 for coal and 20:1 for natural gas. However, more recent studies suggest that technological advancements have pushed solar PV's EROI higher, with some estimates exceeding 20:1 (Leccisi et al., 2016) [2].

### **Land Use and Biodiversity**

Land use impacts of solar PV systems have been a topic of debate. While solar farms require substantial land area, studies like Fthenakis and Kim (2009) [1] have shown that the life-cycle land transformation for PV systems (when including fuel extraction for non-renewables) is comparable to or lower than that of coal power. Moreover, innovative approaches such as agrivoltaics and floating solar farms are further reducing the land use impacts of solar PV (Nayak and Brar 2024) [12].

### **Toxicity and Resource Depletion**

Solar PV manufacturing involves the use of some toxic materials and rare elements, raising concerns about resource depletion and end-of-life management. However, demonstrated that the life-cycle toxicity of PV systems is still significantly lower than that of fossil fuel-based electricity when considering the full fuel cycle, including extraction and processing.

## **COMPARATIVE STUDIES AND FUTURE DIRECTIONS**

Numerous studies have compared the environmental performance of different PV technologies. For instance, Fthenakis et al. (2008) [10] compared the life-cycle GHG emissions and other environmental indicators of various PV technologies, including c-Si, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). They found that thin-film technologies like CdTe had lower life-cycle GHG emissions compared to c-Si, primarily due to less energy-intensive manufacturing processes. (Nayak, 2022) [13].

For the sustainable future, latest innovations of Photovoltaic (PV) panels are getting more environmental friendly day by day. However, pointed out, more research is needed to fully understand the life-cycle impacts of these new technologies, particularly regarding long-term stability and end-of-life management.

In conclusion, the literature on life cycle assessment of solar panels demonstrates that while PV technology offers significant environmental benefits compared to conventional energy sources, there are still areas for improvement throughout the life cycle. Continued research and innovation in manufacturing processes, recycling technologies, and emerging PV materials will be crucial in further reducing the environmental footprint of solar energy.

## **CONCLUSION**

The life cycle assessment of solar panels reveals a complex interplay of environmental impacts from production to disposal. While solar energy offers significant benefits in reducing greenhouse gas emissions during operation, the manufacturing process remains energy-intensive and relies heavily on raw materials extraction. The production phase, particularly silicon purification and panel assembly, contributes substantially to the overall environmental footprint.

However, technological advancements and increased manufacturing efficiency have steadily improved the environmental performance of solar panels. The energy payback time has decreased, and the carbon footprint per kWh generated has diminished over the years. The operational phase demonstrates clear environmental advantages, with minimal emissions and resource consumption compared to fossil fuel alternatives.

In conclusion, while solar panels do have environmental impacts throughout their life cycle, their net benefit in transitioning to cleaner energy sources is evident. Continued research and development in manufacturing processes, material efficiency, and recycling technologies will further enhance the sustainability of solar energy systems.

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