Environmental Assessment of Solar PV Systems Using Life Cycle Analysis

Kannan Kandavelu[1*], Paramaguru. G[2], Anbuchezian Ashokan[3], Silambarasan Rajendran[4]
[1]Department of Electrical and Electronics Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India.
[2]Department of Mechanical Engineering, Tagore Institute of Engineering and Technology, Deviyakurichi, 636112, Tamil Nadu, India.
[3]Department of Civil Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India.
[4]Department of Mechanical Engineering, Annapoorana Engineering College (Autonomous), Seeragapadi, Salem, 636308, Tamil Nadu, India. [4]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.

Abstract
This study presents a comprehensive environmental assessment of solar PV systems using LCA methodology. The results show that although solar PV systems significantly reduce greenhouse gas emissions during their operational phase, considerable environmental impacts arise during manufacturing and material extraction. Among the technologies studied, thin-film modules demonstrate the lowest embodied energy but raise concerns regarding the use of rare and toxic materials. The findings highlight the need for improvements in manufacturing processes, recycling strategies, and material selection to minimize the environmental footprint of PV systems. This research contributes to a deployment and offers recommendations for policymakers and industry stakeholders to enhance the sustainability of solar energy technologies.
Keywords: *Solar Photovoltaic (PV) Systems, Life Cycle Assessment (LCA), Environmental Impact, Energy Payback Time (EPBT), Global Warming Potential (GWP)*

INTRODUCTION

The global shift toward renewable energy has become an imperative in the the depletion of fossil fuels. Among various renewable energy sources, solar photovoltaic (PV) systems have emerged as one of the promising technologies due to their ability to directly convert sunlight into electricity without any moving parts or fuel combustion [1]. The growth of solar PV installations worldwide reflects its increasing importance in achieving a sustainable and low-carbon energy future. While solar PV systems offer substantial environmental advantages during their operational phase such as zero emissions, low noise, and minimal maintenance their entire life cycle includes several stages that may contribute to environmental burdens [2]. These stages include transportation, and a comprehensive evaluation must account, not just the operational phase [3]. Applying LCA to solar PV systems provides insights into the energy consumed and emissions generated during the production and disposal of the components, such as silicon wafers, glass, and metals [4].

This study focuses on conducting a cradle-to-grave LCA of film modules. By quantifying the environmental impacts such as carbon footprint, (EPBT), and (GWP), the research aims to identify the stages and materials with the highest environmental loads. The outcomes of this assessment will help policymakers, engineers, and manufacturers make informed decisions to optimize solar PV and guide future innovations in clean energy technology.

Table 1. State of Research of LCA Studies with Parameters of Renewable Energy Systems

Author(s)	Technology	System Boundary	Key Parameters	LCA Tool/Database	Main Findings
[5]	Solar PV (CdTe, c-Si)	Cradle-tograve	GWP, EPBT, emissions	GaBi, ecoinvent	CdTe has lower GWP
					than crystalline PV
[6]	Solar PV	Cradle-tograve	EPBT, EROI	SimaPro	EPBT: ~1–3 years depending on PV type
[7]	Solar PV	Cradle-tograve	GHG emissions, EPBT	Literature Review	Thin-film has lowest EPBT
[8]	Solar PV	Cradle-tograve	EPBT, EROI	Meta-analysis	Energy return is improving with tech advancements
[9]	Solar PV	Cradle-tograve	CO_2 emissions, land use	SimaPro, Ecoinvent	Impact varies with solar irradiance
[10]	Solar PV (Module design)	Cradle-tograve	EPBT, module materials	Custom LCA model	Module design greatly affects life-cycle results
[11]	PV Solar disposal	End-of-life	Recycling, toxicity	Ecoinvent, GaBi	Recycling lowers lifecycle impacts by ~20%
[12]	PV Technologies	Cradle-tograve	All environmental impact categories	Ecoinvent, OpenLCA	Regional grid mix affects carbon footprint
[13]	Wind, Hydro, Biomass	Cradle-togate	GWP, cost of electricity	Literature-based	Wind and hydro outperform biomass

2. METHODOLOGY

This study to evaluate the environmental impacts associated with solar photovoltaic (PV) systems [14]. Life Cycle Inventory (LCI) data are collected from a combination of peer-reviewed literature, manufacturer data, and reputable LCA databases such as Ecoinvent and OpenLCA. The inputs considered include materials such as silicon, glass, aluminum, and electricity, while outputs include greenhouse gas emissions, waste generation, and resource consumption. Using LCA software tools like SimaPro and OpenLCA, the study quantifies impacts across categories [15]. The interpretation phase focuses on identifying environmental hotspots, comparing the environmental performance of the selected PV technologies, and recommending improvements for sustainable design and policy implementation.

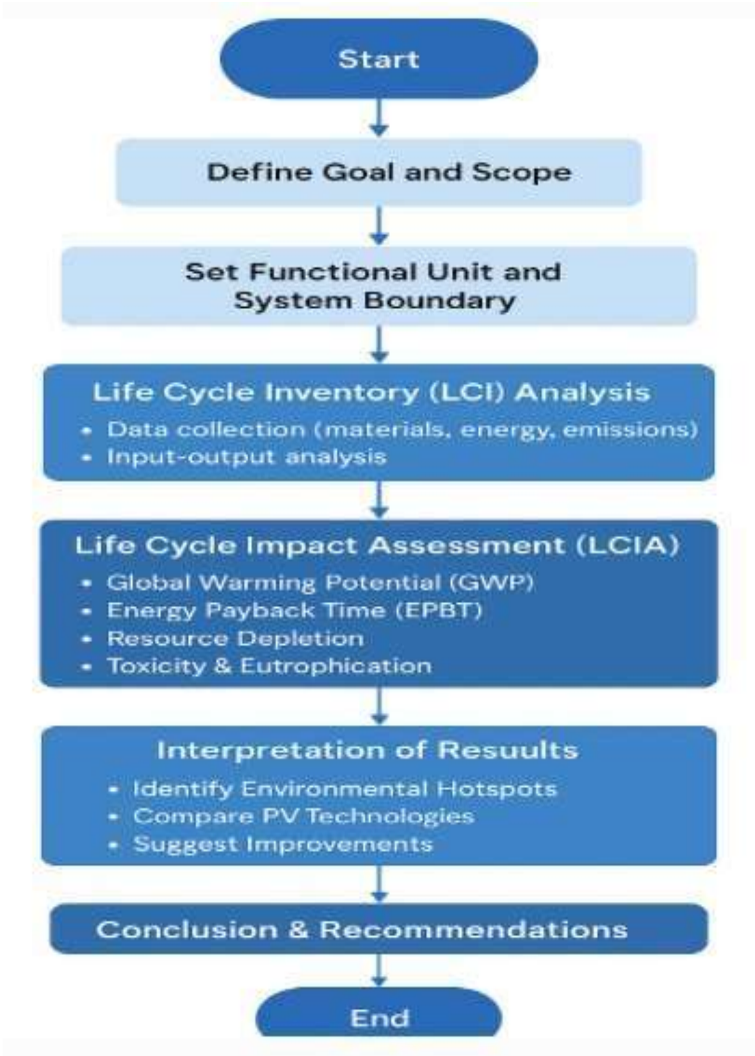

Fig. 1. Framework of Life Cycle Assessment

3. Life Cycle Inventory (LCI) Analysis

The purpose of the LCI is to identify the energy, material, and emission flows that occur throughout the system boundary defined in the scope of the study [16]. LCI data are gathered from a combination of secondary sources such as scientific literature, manufacturer technical datasheets, and recognized databases including Ecoinvent, GaBi, and OpenLCA. The data includes the quantity and type of materials used (e.g., silicon, glass, aluminum, copper, encapsulants), the energy consumed during manufacturing processes (typically electricity from various sources), and the emissions released into air, water, and soil [17].

Each solar PV technology monocrystalline, polycrystalline, and thin-film—has unique material and energy requirements. For example, monocrystalline panels require high-purity silicon, resulting in higher energy inputs during the crystal growth and wafer slicing processes. In contrast, thin-film modules use smaller quantities of semiconducting materials but may involve toxic elements.

The inventory also includes:

- **Transportation** impacts based on distance, mode (truck, rail, sea), and fuel consumption.
- **Installation phase** components such as mounting structures and inverters.
- **Operational phase** impacts are minimal but include inverter losses and occasional maintenance activities.
- **End-of-life** data includes disposal, potential recycling rates, and emissions from waste handling.

All data are normalized to installed solar PV system, ensuring consistency and comparability across technologies. The resulting inventory serves as the foundation for the subsequent LCIA phase are quantified [18].

4. Life Cycle Impact Assessment (LCIA)

The LCIA phase is a critical step in the LCA methodology, are translated into potential environmental impacts. In this study, LCIA is applied to evaluate the environmental burdens associated with solar PV systems, focusing on three major technologies [19]. The assessment is conducted using internationally accepted are CML, ReCiPe, or TRACI, depending on software compatibility (e.g., SimaPro, OpenLCA). These methods classify and characterize emissions and resource usage into specific environmental impact categories.

The key impact categories considered include:

- **GWP:**
  Measures the contribution of greenhouse gas emissions to climate change, expressed in kg CO_2equivalent per functional unit.
- **EPBT:**
  Represents lower EPBT indicates a more sustainable system.
- **Resource Depletion:**
  Quantifies materials and rare metals (e.g., indium, tellurium) and fossil fuels.
- **Acidification Potential:**
  SO_2 and NO_x to form acid rain.
- **Eutrophication Potential:**
  Measures the nutrient loading of aquatic environments caused by emissions such as phosphates and nitrates, leading to oxygen depletion and ecosystem imbalance.
- **Human Toxicity and Ecotoxicity:**
  Evaluates the harm to human health and ecosystems due to substances like heavy metals, solvents, and toxic gases.

The analysis reveals that while operational emissions from PV systems are nearly zero, the manufacturing stage contributes significantly to the total environmental impact, particularly in energy use and GWP. Thin-film technologies tend to have lower energy requirements but may pose environmental risks due to toxic elements like cadmium.

The results of the LCIA are different PV technologies, identify major contributors to environmental burden (hotspots), and propose recommendations for cleaner production, material substitution, and improved end-of-life strategies.

5. RESULTS AND DISCUSSION

The findings from the LCIA of three solar photovoltaic (PV) technologies on a 1 kWp system over a 25-year operational life. The results including GWP5, EEPBT, resource depletion, and impacts. Each technology is evaluated across all transportation, installation.

5.1. Global Warming Potential (GWP)

Monocrystalline silicon modules showed the highest GWP, averaging around 950–1100 kg CO_2eq/kWp, primarily due to high electricity consumption during silicon purification and wafer cutting. Polycrystalline systems performed moderately with 700–850 kg CO_2-eq/kWp, while thin-film systems exhibited the lowest GWP values, typically below 600 kg CO_2-eq/kWp, attributed to reduced material and energy use. However, the lower GWP of thin-film must be weighed against its higher toxicity and resource concerns [20].

5.2.EPBT

The reflects the efficiency of energy investment. Monocrystalline systems had the longest EPBT of around 2.5–3.0 years, while polycrystalline systems averaged 2.0–2.5 years. Thin-film modules had the lowest EPBT, typically <1.5 years, due to thinner absorber layers and simplified manufacturing processes. These findings suggest that thin-film technologies can deliver energy more efficiently over their lifetime but must be assessed for material sustainability.

5.3. Resource Depletion and Toxicity

Although monocrystalline and polycrystalline modules consume more silicon and energy, they utilize relatively abundant and non-toxic materials. In contrast, thin-film technologies (e.g., CdTe, CIGS) often involve scarce and potentially hazardous elements like cadmium, indium, and tellurium. The environmental burden in thin-film production is therefore more chemical-intensive, raising concerns regarding end-of-life treatment and recycling (Figure 2).

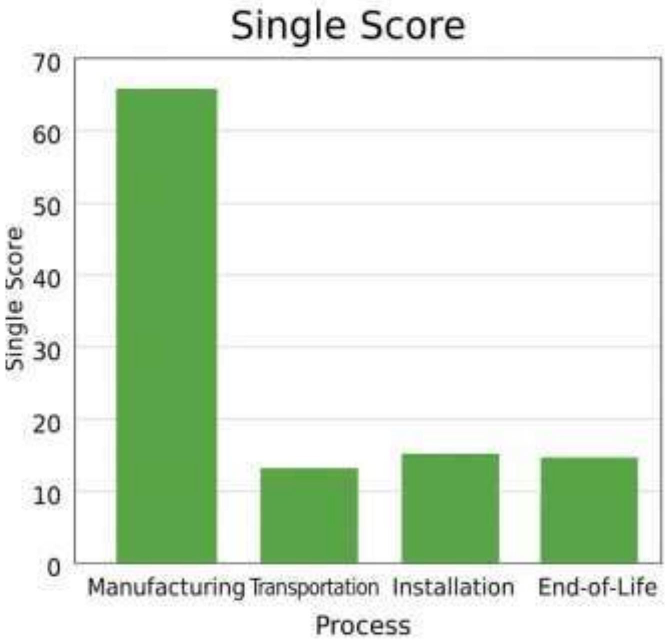

Figure 2. Single score graph comparing processes

5.4. End-of-Life and Recycling Potential

The results emphasize the significance of recycling in reducing lifecycle impacts. Recovery of materials like aluminum frames, glass sheets, and silicon wafers can reduce GWP by up to 20%, depending on the efficiency of the recycling process. Thin-film modules, while difficult to recycle, can still benefit from targeted collection and closed-loop material recovery systems. The comparative LCA results clearly indicate that no single PV technology is environmentally superior in all categories. Monocrystalline systems, while mature and efficient, are energy-intensive to produce. Thin-film modules offer advantages in GWP and EPBT but face challenges related to material toxicity and recyclability. The findings suggest that technology selection should be context-dependent, based on local energy sources, end-of-life infrastructure, and specific environmental priorities.

Furthermore, environmental impacts can be significantly reduced by:

- Sourcing cleaner electricity during manufacturing (e.g., using renewables)
- Improving material efficiency and design for recyclability
- Enhancing collection and recycling schemes for decommissioned panels

The results validate the need for policy interventions, eco-design standards, and extended producer responsibility (EPR) to support the environmental sustainability of solar PV systems throughout their life cycle.

CONCLUSION

This study conducted a comprehensive environmental assessment of PV systems using LCA methodology. The research provides a clear understanding PV system. The findings reveal that while all three PV technologies significantly reduce emissions during their operational phase, the manufacturing stage remains the primary contributor to environmental impacts, particularly in terms of GWP and energy consumption.

Among the technologies assessed, thin-film modules exhibited the lowest GWP and energy payback time (EPBT). In contrast, monocrystalline systems, though more energy-intensive to manufacture, offered better recyclability and maturity in deployment.

The study concludes that there is no universally superior PV technology; instead, the environmental performance depends on factors such as material sourcing, manufacturing energy mix.

To enhance the sustainability of PV systems, strategies such as greener manufacturing practices, use of low-carbon energy sources, **eco-**design, and effective recycling mechanisms must be implemented. Overall, this research supports the continued adoption of solar PV technologies while emphasizing the importance of minimizing their life cycle impacts. The insights generated from this study, manufacturers, informed decisions to promote clean, efficient, and environmentally responsible solar energy systems.

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