The Climate Footprint of Clean Energy: A Cradle-to-Grave Life Cycle Assessment of a Photovoltaic System

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Abstract. The global transition to solar photovoltaics (PV) is essential for achieving the Sustainable Development Goals for climate action (SDG 13) and clean energy (SDG 7). However, the true environmental viability of PV technology hinges on its full lifecycle performance. This study conducts a cradle-to-grave Life Cycle Assessment (LCA) of a complete utility-scale monocrystalline PV system, including Balance of System (BOS) components such as the 1-axis tracker, inverter, transformer, and associated electrical-mechanical hardware. The analysis, in the context for manufacturing with the West-India electricity grid mix, follows ISO 14040 standards with a functional unit of 1 m^2 of the system operated for 30 years. The assessment reveals that across key impact categories, pre-operational stages overwhelmingly dominate the environmental profile. This investigation identifies two primary hotspots: the energy-intensive manufacturing of the PV module, and the material-intensive production of the BOS. The findings highlight that the environmental credentials of solar PV are very closely linked to the decarbonization of the manufacturing supply chain for all system components.

1 Introduction

The global energy sector is undergoing a major transformation as countries come together to address climate change. In response to global climate agreements, governments around the world have been strengthening their efforts to curb carbon emissions and accelerate the shift from fossil-fuel-based systems to renewable energy technologies. Among available renewable options, solar photovoltaics (PV) have emerged as a prominent solution for generating clean energy [1-3]. The growth of solar power has been remarkable, with about 456 GW of new PV capacity added worldwide in 2023 [4]. With costs declining and policies becoming more favourable, the sector’s rapid growth illustrates how crucial solar

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technologies have become for achieving broader sustainability goals and advancing clean-energy transitions worldwide [5].

To ensure this rapid deployment genuinely contributes to sustainability without creating unforeseen environmental burdens, an all-inclusive evaluation of PV technology is essential. Life Cycle Assessment (LCA) offers a consistent and scientifically robust approach for ~~conducting such evaluations [6]. Interna~~tional standards like ISO 14040 govern LCA, requiring the assessment of a product's entire life cycle, from the acquisition of raw materials through manufacturing, use, and eventual disposal [7-9]. This thorough approach is vital for avoiding "problem-shifting," where solving an environmental issue in one stage unintentionally creates a new problem elsewhere, such as challenges in recycling or reliance on toxic materials [7,10].

While numerous LCA studies on PV systems exist, their findings report a significant variability in key metrics like the carbon footprint [6]. This variation is not random; it is heavily influenced by a combination of technological and regional factors. A key factor is the carbon intensity of the electricity supply used in the energy-demanding process of producing high-purity silicon [11-13].

This variation in reported impacts also indicates that the performance of modern PV systems is still not well understood in geographical and operational settings beyond the commonly studied regions of Europe and China [14]. To address this gap, this study examines the cradle-to-grave impacts of a utility-scale monocrystalline PV installation using a life cycle inventory tailored to Indian manufacturing and grid conditions. Incorporating region-specific data provides an important reference point for one of the fastest-growing solar markets globally [2]. In doing so, the study offers a timely benchmark that can support policymakers, industry practitioners, and researchers engaged in planning the long-term, sustainable expansion of renewable energy systems.

2 Life Cycle Assessment

LCA is an established scientific approach that enables a complete evaluation of environmental impacts by examining every stage of a product's life, from material sourcing to disposal. The methodology is structured into four iterative phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation (LCIn). Such a broad framework is essential for energy systems, since improvements in operational performance can sometimes shift burdens upstream to material extraction or component manufacturing [11].

The assessment was carried out using openLCA. Process-specific data from recent research were combined with information from the Ecoinvent 3.11 database to create a comprehensive life cycle inventory. Environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method, which offers wide coverage of relevant impact categories and relies on well-established characterization factors.

2.1 Goal and Scope Definition

The primary objective of this study is to carry out a full life-cycle assessment of a modern monocrystalline PV system, examining its environmental impacts and resource demands over its complete life. For consistency and comparability, the functional unit is defined as 1 m^2 of a utility-scale monocrystalline system, produced and operated over a 30-year service life.

The analysis adopts a full cradle-to-grave scope, as shown in Figure 1, covering the entire utility-scale system to develop a practical and comprehensive environmental profile. The system boundary therefore includes PV panel as well as the essential Balance of System (BOS) components, such as the 1-axis tracker, inverter, transformer, and associated electrical hardware. Adopting a system-level approach is essential to ensure that significant environmental impacts from structural and electrical components are not neglected. The system boundaries cover all lifecycle stages, including the mining and pre-processing of primary raw materials; the entire manufacturing process from polysilicon production to final module assembly; a simplified 30-year operational phase; and an end-of-life (EoL) scenario based on landfilling. Figure 2 represents the life cycle framework used for the environmental analysis.

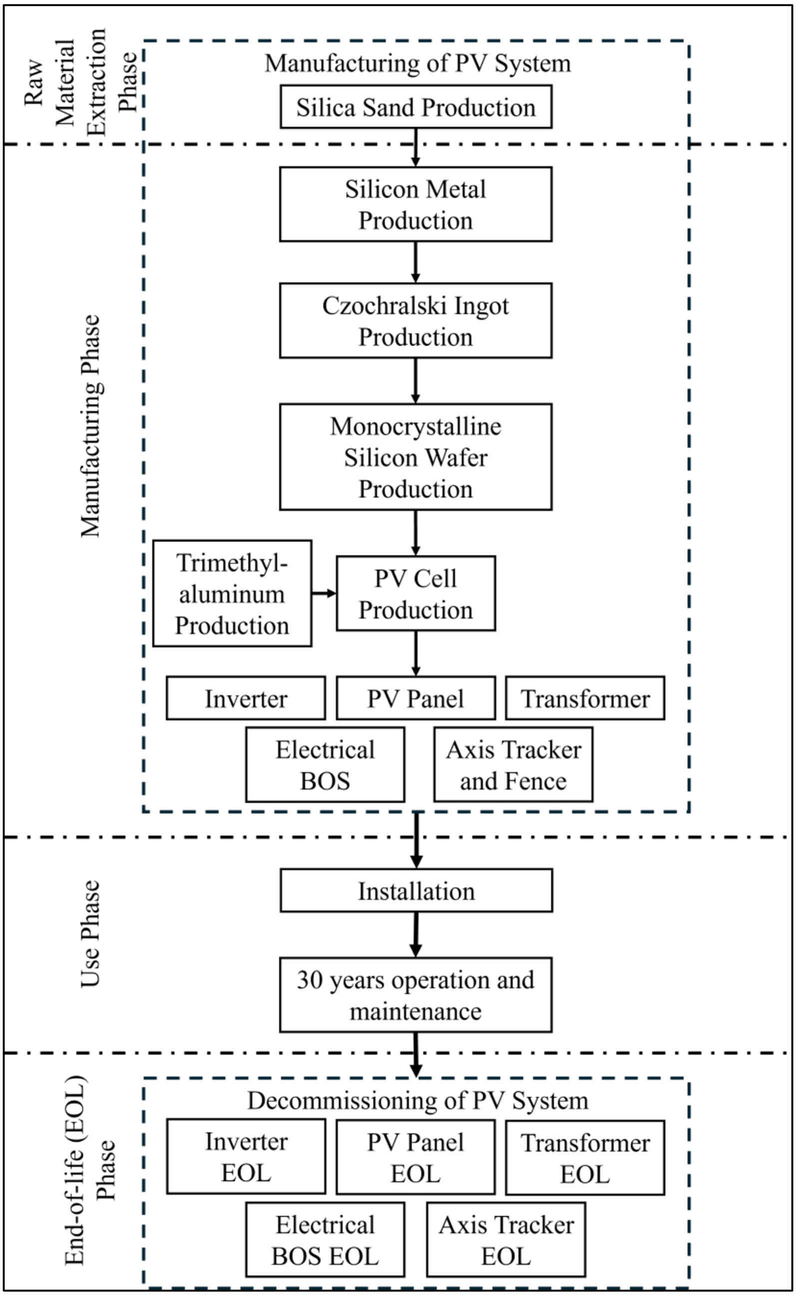

Figure 1. Cradle-to-grave System Boundary for a PV module.

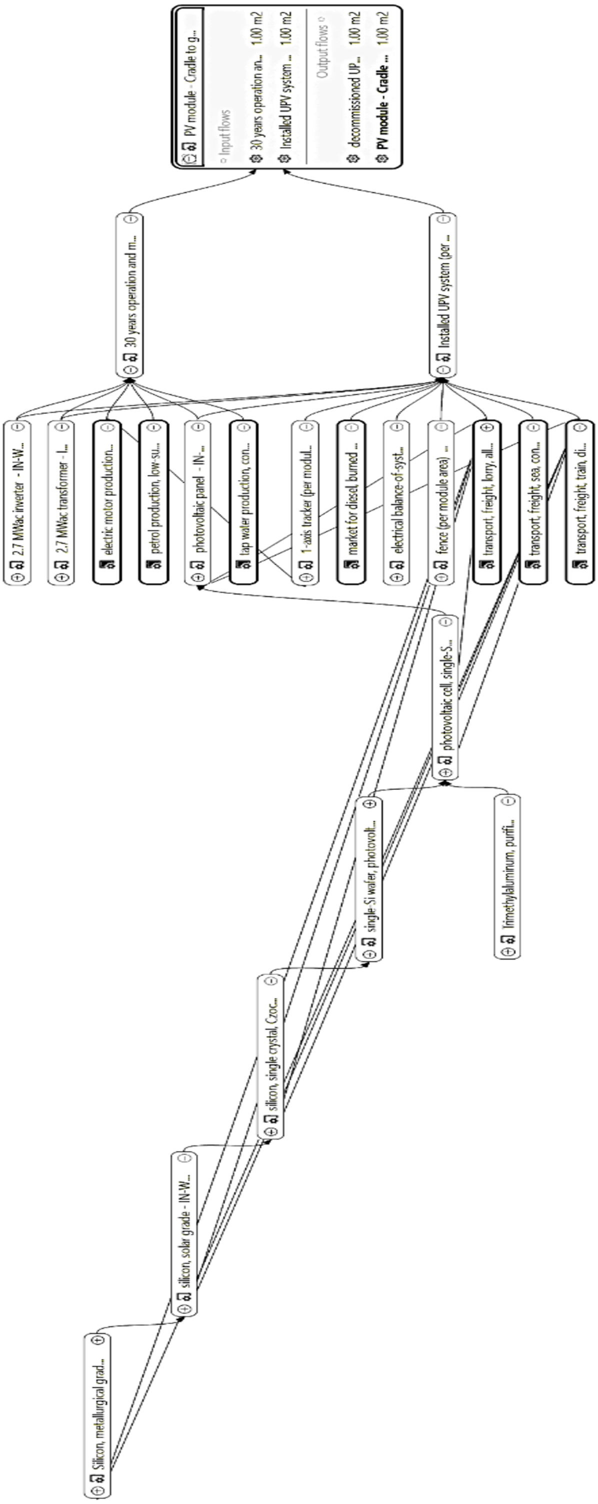

Figure 2. Life Cycle Framework of PV Module.

2.2 Life Cycle Inventory (LCI)

The LCI stage involves systematic gathering and quantification of all inputs and outputs of materials, energy, and waste for each process within the defined system boundaries. A hybrid modelling approach was employed, integrating data from recent scientific literature with data from the Ecoinvent 3.11 database. This approach ensures that the inventory remains both comprehensive and representative of current industrial practices in PV module manufacturing.

To improve regional relevance, all electricity-driven processes were modelled using the Western Indian grid mix, which relies heavily on fossil-fuel generation. We also assumed domestic sourcing and predominantly truck- and rail-based transport to avoid inflating impacts through unnecessary international freight. The LCI was organized into four primary life cycle stages: Production, Installation, Use (Operation and Maintenance), and End-of-Life (EoL). Table 1 summarizes the data sources and modelling references used for each stage.

Table 1. Data Sources and Modelling References for LCI

Life cycle Stage	Process / Component	Data Source(s)
Manufacturing	Silica Sand Production	[15]
	Silicon Metal Production	[9,15-17]
	Polysilicon Production	[14,16]
	Czochralski (Cz) Ingot Production	[9,14]
	Monocrystalline Silicon Wafer Production	[9,14]
	Trimethylaluminum Production	[14]
	PV Cell Production	[9,14]
	PV Module Production	[9,14]
	Single-Axis Tracker	[23]
	Inverter	[8]
	Transformer	[18]
	Cables, Conduits, and Other Electrical BOS	[16]
	Fencing / Site Infrastructure	[18]
Installation	Installation Activities	[9,18]
Use (Operation & Maintenance)	Routine Operations and Maintenance	[12,19–21]
End-of-Life (EoL)	Decommissioning	[18]
	PV Module Landfilling	[22]
	EoL of BOS Components	[16,23]

2.3 Life Cycle Impact Assessment (LCIA)

After completing the inventory analysis, the LCIA was conducted to convert the collected information on material use, energy consumption, and emissions into measurable environmental impact indicators. The ReCiPe 2016 Midpoint (H) method was employed due to its wide-ranging coverage of environmental, human health, and resource-related impacts. Midpoint indicators capture impacts at an intermediate point in the causal chain, such as climate change expressed in CO_2-equivalent units. The specified results of this evaluation are shown in Table 2.

Table 2. Overall Lifecycle Impact Assessment Results per 1 m^2 of a Utility-Scale PV System.

Impact categories	**Results**	**Unit (kg-Eq)**
Climate change	96.93246	CO_2
Ecotoxicity: marine	26.47456	1,4-DCB
Ecotoxicity: freshwater	19.20387	1,4-DCB
Ecotoxicity: terrestrial	665.7619	1,4-DCB
Acidification: terrestrial	0.46532	SO_2
Eutrophication: marine	0.0088	N
Eutrophication: freshwater	0.04237	P
Ionising radiation	12.49535	Co-60
Human toxicity: non-carcinogenic	382.9373	1,4-DCB
Human toxicity: carcinogenic	297.6593	1,4-DCB
Energy resources: non-renewable, fossil	26.7108	oil
Material resources: metals/minerals	9.8219	Cu
Ozone depletion	0.0001	CFC-11
Particulate matter formation	0.20567	PM2.5
Photochemical oxidant formation: terrestrial ecosystems	0.30392	NO_x
Photochemical oxidant formation: human health	0.30863	NO_x
Land use	5.49085	m^2*a crop
Water use	3.6034	m^3

2.4 Life Cycle Interpretation (LCI)

In the last phase, the assessment integrates quantitative findings from the LCI and LCIA to pinpoint key environmental hotspots and derive insightful conclusions. Figure 3 showcases the environmental impacts in five key impact categories.

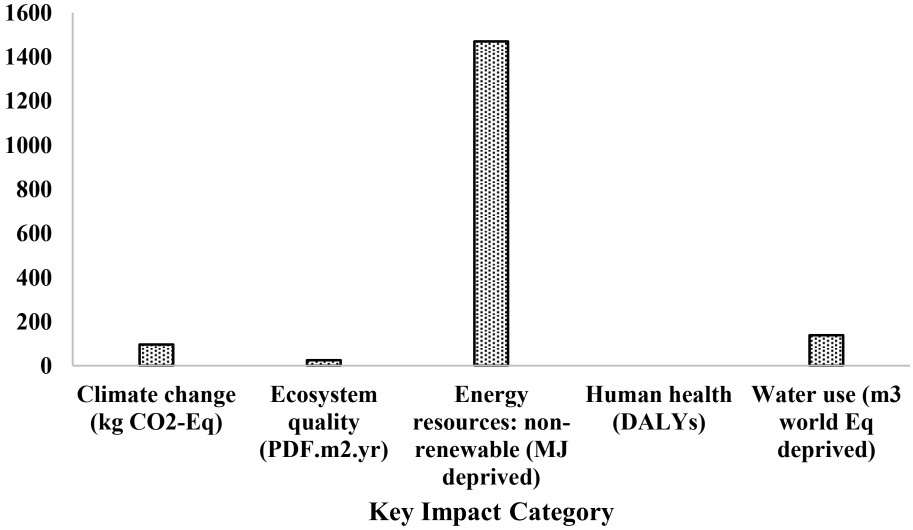

Figure 3. Environmental performance of PV module in five key impact categories.
From the con

tribution analysis, it is clear that the pre-operational steps, including material extraction, manufacturing, and transport, drive most of the environmental impacts observed in every category. The operational use phase and the EoL landfilling scenario have a comparatively minor contribution. The primary hotspots within the system are the PV Panel itself, the 1-Axis Tracker, and the Transformer.

An analysis of the contribution data reveals important details. For Climate Change, the PV Panel is the dominant contributor, responsible for 53.7% of the total impact, followed by the 1-Axis Tracker (29.5%) and the Transformer (6.75%). However, for other impact categories, the structural components play a more significant role. In Freshwater Ecotoxicity, the tracker's contribution (34.4%) is nearly equal to the panel's (37.3%). The tracker is also a major contributor to Human Toxicity: non-carcinogenic (39.6%) and Material Resources: metals/minerals (54.5%). Notably, in categories like Ozone Depletion, the PV Panel's contribution is exceptionally high (86.0%), while for Photochemical Oxidant Formation, transportation becomes a more relevant factor (over 14%). This detailed distribution of impacts across system components would be best visualized in a stacked bar chart (Figure 3).

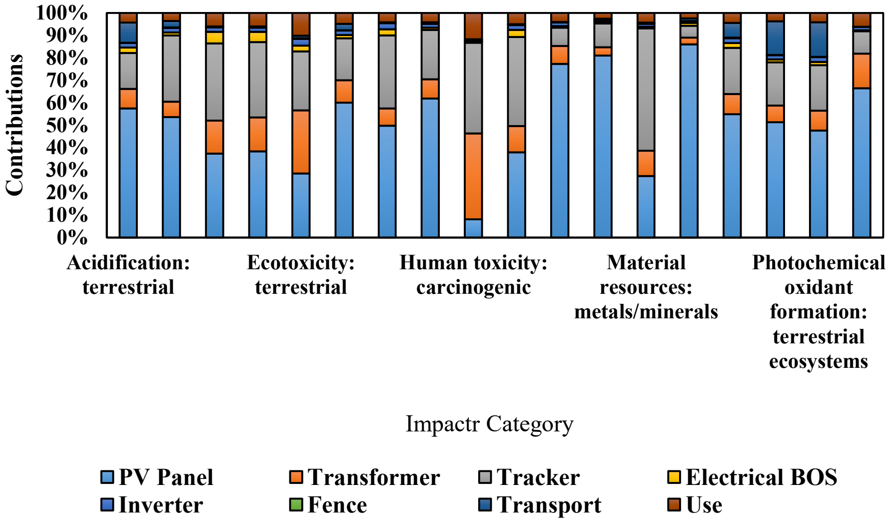

Figure 3. Relative contribution of PV system components to total lifecycle environmental impacts.

3 Conclusions

This LCA of a utility-scale monocrystalline PV system leads to some key conclusions:

- The largest share of the system's environmental impacts arises from the pre-operational stages, such as raw material extraction and component manufacturing, while the operational use phase and EoL stage contribute relatively low.
- The total lifecycle burdens per m^2 of the system include 96.93 kg-Eq. (Climate Change), 26.71 kg oil-Eq. (Fossil Resource Scarcity), and 3.60 m^3 (Water Consumption). The analysis identified two primary hotspots responsible for these impacts: the PV Panel and the 1-Axis Tracker.
- The contribution analysis reveals shifting hotspots across impact categories, reinforcing the need for a system-level view. While the PV Panel dominates the

climate change impact (53.7%), the 1-Axis Tracker's contribution is nearly equal in Freshwater Ecotoxicity (34.4% vs. the panel's 37.3%). Furthermore, the panel is almost solely responsible for Ozone Depletion (86.0%), while transportation becomes a notable factor in Photochemical Oxidant Formation (over 14%).
- The high embodied impacts in the manufacturing stage are a direct consequence of the reliance on the fossil-fuel-dominant Indian electricity grid for energy-intensive processes like polysilicon purification and ingot growth.

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