Life Cycle Carbon Footprint Assessment of Solar Photovoltaic Systems in US and China

by

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EXECUTIVE SUMMARY

This report presents a comprehensive life cycle assessment (LCA) of the carbon footprint of solar photovoltaic (PV) systems, with a focus on comparative emissions between systems manufactured in China and the United States. As global demand for renewable energy rises, understanding and reducing the environmental impacts of solar technologies becomes essential to support sustainable energy transitions and climate goals.

The study evaluates carbon emissions across six key life cycle stages: raw material extraction, component manufacturing, transportation, installation, operation and maintenance, and end-of-life management. Results show that the manufacturing stage dominates, contributing over 88% of total emissions per module, primarily due to energy-intensive processes such as silicon purification and aluminum production.

Despite China's leadership in global PV manufacturing, its heavy reliance on coal-based electricity results in higher emissions (490 kgCO_2e/module) compared to the U.S. (476 kgCO_2e/module). However, China's large-scale industrial efficiency provides slight advantages in emissions per module for certain components like glass.

This analysis also highlights regional differences in regulatory enforcement, energy mix, and policy incentives, including the impact of U.S. initiatives like the Inflation Reduction Act. While transportation, installation, and end-of-life stages contribute less to overall emissions, they offer additional opportunities for improvement through cleaner logistics and enhanced recycling practices.

The report recommends that future efforts prioritize decarbonizing upstream manufacturing, improving data transparency, and exploring new technologies and circular economy strategies. A globally harmonized approach to life cycle emissions reductions in PV systems is vital for achieving long-term climate targets.

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I. INTRODUCTION

As global energy demand continues to rise, there is a growing transition away from fossil fuels like oil, natural gas, and coal and toward renewable energy. This transition is driven by the environmental consequences of fossil fuel consumption. It is responsible for roughly 75% of global greenhouse gas emissions and 90% of total carbon dioxide emissions (United Nations, n.d.). The significantly lower manufacturing costs and the absence of fuel expenses associated with solar panels underscore the advantages of solar power as a key player in the transition to renewable energy (United Nations, n.d.).

Prior research has shown that over the lifespan of a photovoltaic (PV) system, each 0.65 m^2 silicon panel requires a total energy demand of 1494 MJ/panel for its production and emits 80 kilograms of CO_2, contributing to global warming (Stoppato, 2008). The pivotal steps include the transformation of silicon metal into solar silicon and the subsequent construction of the panels (Stoppato, 2008). While solar energy itself is carbon-free during operation, the overall carbon footprint of PV systems is often assumed to vary significantly across regions due to differences in manufacturing practices, energy sources, and regulatory frameworks. However, this study investigates that assumption and finds the regional variation to be relatively modest under certain scenarios. Consequently, a detailed analysis of the carbon footprint at each stage of the PV system's life cycle is vital to understanding and mitigating global environmental impacts.

China and the United States serve as critical case examples for this approach. China, the foremost participant in the worldwide photovoltaic industry, capitalizes on its enormous manufacturing capabilities and robust governmental support, including subsidies and a well-developed supply chain network (International Energy Agency, 2022). Nonetheless, the country's dependence on coal-derived energy for the production of photovoltaic systems poses significant environmental issues. Peng et al. (2013) emphasized that regions with cleaner energy grids, such as those powered by hydroelectric or wind energy, exhibit lower carbon emissions during the manufacturing phase. For example, the greenhouse gas emission rate of the Norwegian energy system was not significant, as the majority of electricity in the country was produced from hydropower (Peng et al., 2012). In contrast, areas with a high reliance on fossil fuels have higher emissions. Performing a life cycle carbon footprint assessment in China is essential for precisely measuring these effects and investigating ways for shifting to cleaner and more sustainable industrial practices. The US holds the second-largest share of the global PV market, propelled by robust incentives such as the Investment Tax Credit (ITC) and Renewable Energy and Energy Efficiency Portfolio Standards (REPS). These incentives not only support the market but also encourage the adoption of cleaner energy sources in the manufacturing process, potentially reducing the carbon footprint of PV systems. Therefore, a comparative assessment is essential for improving the sustainability of the photovoltaic business, offering data that may assist policymakers and industry stakeholders like solar developers in making educated decisions regarding solar energy.

The Inflation Reduction Act highlights the importance of building a clean energy economy to tackle the climate crisis (FACT SHEET: How the Inflation Reduction

Act's Tax Incentives Are Ensuring All Americans Benefit From the Growth of the Clean Energy Economy, 2024). This study directly supports the national objective by focusing on the two leading countries in solar PV production (IEA PVPS Reporting Countries, Becquerel Institute et al., 2024). Analyzing their respective carbon footprints offers valuable insights into strategies for reducing greenhouse gas emissions, fostering sustainable energy transitions, and addressing the global climate challenge.

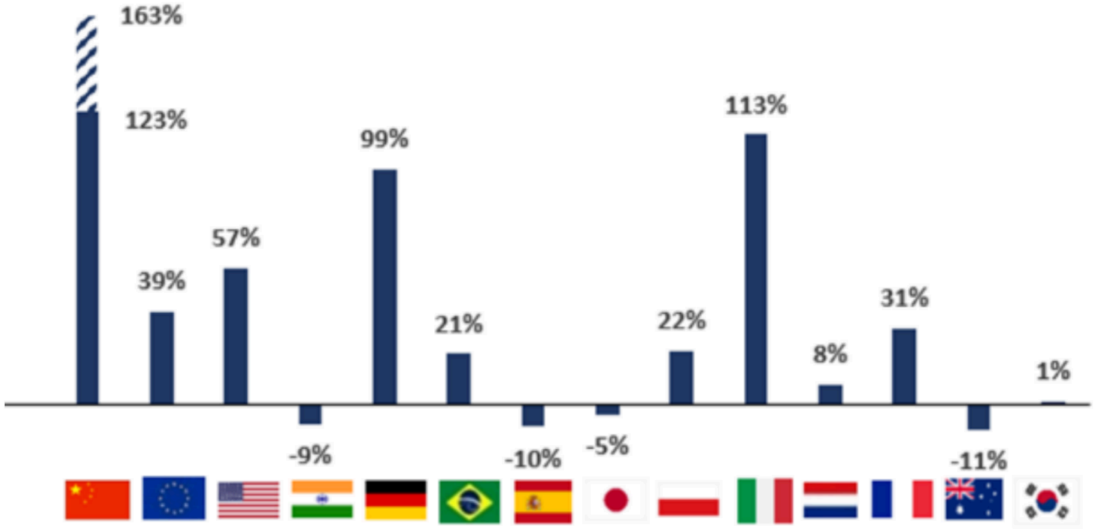

Figure 1. Evolution of New Annual Capacity in Major Markets 2022-2023

Furthermore, an examination of the carbon emissions associated with the supply chains of solar PV systems essentially can clarify the potential risks in terms of environmental management and protection. By conducting a comparative analysis, this study can gain insights into how these variations shape the life cycle emissions of solar panels and explore potential avenues for reducing their environmental impact through optimized manufacturing practices.

1.1-Objective

This study will address the following questions:

(1) What is the carbon footprint of solar photovoltaic (PV) systems throughout their entire life cycle?

With the following subquestions:

(2) Which stage contributes the most proportion of carbon footprint among life cycle assessments?

(3) How do regional factors, including grid mix, environmental standards, and efficiency of manufacturing practices, affect the carbon footprint of solar photovoltaic (PV) systems' supply chains in China and the US?

II. LITERATURE REVIEW

As solar power continues to expand globally, assessing the life cycle carbon footprint of PV systems has become a key focus of research. This section explores previous studies on the carbon emissions associated with each stage of the PV life cycle, including material extraction, manufacturing, transportation, installation, operation, and end-of-life management. Based on the six stages above, the photovoltaic life cycle has three principal phases: (1) Upstream—material extraction, manufacture, transportation, and installation; (2) Operational—energy generation; and (3) Downstream—end-of-life management.

2.1-Eco-Impacts of Solar Panels Over Their Life Cycle

Research into the eco-impacts of solar panels has consistently highlighted the importance of different life cycle stages in determining their overall environmental footprint. The majority of greenhouse gas (GHG) emissions in PV systems occur upstream in materials and PV module manufacturing, especially in the production of high-purity silicon for crystalline silicon modules (Bošnjaković et al., 2023). This energy-intensive process involves silicon purification, wafer production, and cell assembly, which requires significant amounts of electricity. The environmental impact of these stages is largely influenced by the energy mix used in manufacturing facilities, with coal-dominated grids contributing substantially higher emissions compared to regions with cleaner energy sources (Hsu et al., 2012). Fthenakis et al. (2008) demonstrated this by analyzing various electricity mix scenarios for silicon production, showing that switching from a hydropower and natural gas-based mix to a U.S. electricity grid mix, which relies on over 50% coal, results in an approximately 50% increase in GHG emissions from crystalline silicon (c-Si) modules.

Beyond silicon production, module assembly also contributes to the carbon footprint due to the use of materials such as aluminum frames, glass, and encapsulation layers. Studies have shown that approximately 65% of the life cycle GHG emissions of a PV system can be attributed to these upstream stages (Zhang et al., 2024). This highlights the critical need for manufacturers to adopt energy-efficient production techniques and integrate renewable energy into their operations to reduce the environmental impact.

Recent advancements in PV technology, such as thin-film solar cells, present opportunities to reduce the environmental and human health impacts of solar panels. These technologies generally require less energy and fewer materials in their production, resulting in lower life cycle emissions, ease of manufacturing, and competitive environmental indicators (Kim et al., 2012). The published and harmonized life cycle greenhouse gas emissions statistics demonstrate that the carbon footprint of thin-film photovoltaic technologies markedly diminishes with increased manufacturing capacity, indicative of technical advancements in processes and device designs (Kim et al., 2012).

In conclusion, whereas solar panels offer substantial environmental advantages throughout their operating phase by producing clean electricity, the upstream phases of their life cycles represent a critical area for improvement. By mitigating the energy and material intensity of production and improving recycling initiatives, the total ecological impact of photovoltaic systems may be significantly diminished, expediting the shift toward a more sustainable energy future.

2.2-PV Manufacturing in the US vs. China

In 2021, the worldwide production capacity for solar photovoltaic modules reached 250 GW. China currently dominates the market, commanding at least 80% of the supply chain, with forecasts suggesting this might increase to 95% in the manufacture of polysilicon, ingot, and wafer (International Energy Agency, 2022). China's dominance is attributed to its large-scale production capacity, government subsidies, and extensive supply chain networks. In contrast, the US's smaller share is due to higher labor and energy costs for domestic manufacturing. These differences may influence the eco-impacts of solar panels produced in each country.

Environmental policies and enforcement also vary significantly between the US and China, particularly in the context of manufacturing industries. In the U.S., environmental regulations are often more stringent in sectors such as energy, manufacturing, and chemicals, while China enforces stricter regulations in transportation and agriculture (Xu & Wiener, 2021).

However, the enforcement of these regulations can vary across regions within China, leading to inconsistencies in environmental performance. In contrast, the U.S. often relies on market-driven approaches and state-level policies, resulting in variability in environmental performance across manufacturers (Xu & Wiener, 2021). Market-based approaches, such as cap-and-trade systems, carbon taxes, and renewable energy credits, incentivize manufacturers to reduce emissions cost-effectively. For instance, recent analyses continue to demonstrate the effectiveness of cap-and-trade systems in reducing sulfur dioxide (SO_2) emissions under the Acid Rain Program. The U.S. Environmental Protection Agency (EPA) reports that since the program's inception in 1995, there has been a significant decrease in SO_2 emissions from power plants, achieving substantial environmental benefits at costs lower than initially projected (*Acid Rain Program | US EPA*, 2024). These mechanisms allow flexibility in achieving environmental targets while fostering innovation in cleaner production technologies.

State-level policies also play a crucial role in shaping the environmental impacts of PV manufacturing across the United States. While 24 states plus the District of Columbia have set specific greenhouse gas emissions targets, the implementation and effects of these policies can vary significantly, influencing how manufacturers operate within these jurisdictions, as shown in **Figure 2** (Centre for Climate and Energy Solutions, 2023). For example, California's stringent environmental regulations, embodied in the California Global Warming Solutions Act, not only mandate ambitious GHG reduction targets but also directly impact local manufacturing practices by promoting the use of renewable energy and cleaner production technologies (*AB 32 Global Warming Solutions Act of 2006 | California Air Resources Board*, 2018). Similarly, North Carolina's Renewable Energy and Energy Efficiency Portfolio Standard (REPS) requires utilities to source a portion of their energy from renewable sources, indirectly fostering a market for locally produced, environmentally friendly PV products (*North Carolina Utilities Commission: Clean Energy and Energy Efficiency Portfolio Standard*, n.d.). This policy has led to increased investments in solar energy, enhancing the environmental credentials of manufacturers within the state. In contrast, states like Wyoming and Arizona, with less stringent GHG policies and fewer renewable mandates, may see a slower adoption of such environmentally beneficial manufacturing practices. This variability underscores the significant influence of state-level policies on the ecological footprint of the PV manufacturing industry across different regions, creating a diverse landscape of environmental performance and compliance within the United States.

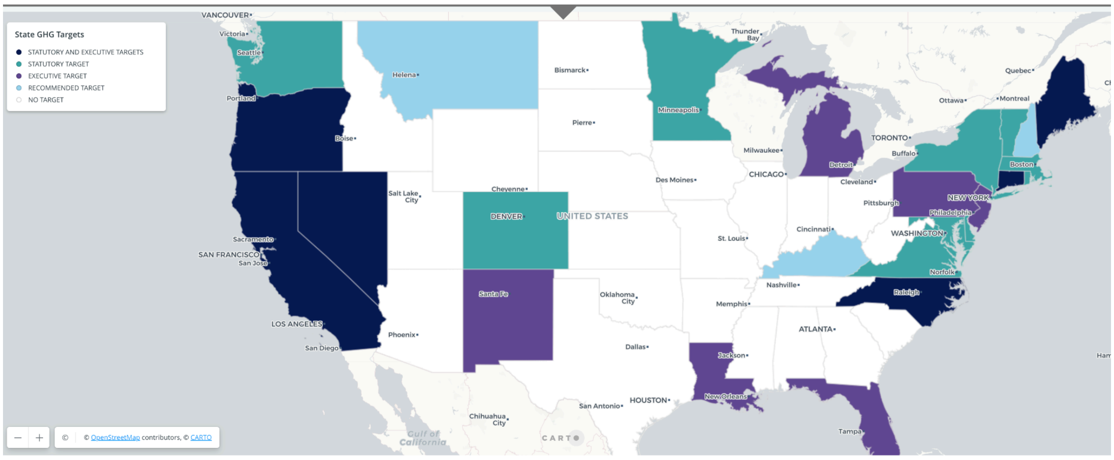

Figure 2. States of Greenhouse Gas Emissions Targets
https://www.c2es.org/content/state-climate-policy/

Research from other industries suggests that Chinese manufacturers may adopt eco-friendly practices to comply with European regulations, potentially resulting in lower carbon footprints than some US counterparts (Stanway, 2024). For instance, China's steel industry has accelerated its shift toward greener production methods in response to the EU's impending carbon levy on exports (Stanway, 2024). In the first half of 2024, only cleaner electric arc furnace (EAF) projects were approved, with no new coal-based steel projects, potentially reducing CO_2 emissions by 200 million metric tonnes by 2026 (Stanway, 2024). However, in sectors with less stringent export requirements, Chinese manufacturing may have higher emissions due to reliance on coal-based energy. The US's relatively cleaner energy mix and stronger enforcement of certain federal regulations, such as the Clean Air Act, could offer advantages in terms of eco-impacts for domestically produced panels.

III. METHODS

To provide an overview of the PV system's value chain and help understand the context of the detailed stages that follow, especially potential stakeholders, inputs, outputs, and the value added in each stage, a value chain map of the PV system is included, as shown in **Figure 3**.

Value Chain Map of PV Systems				
	Stakeholders	Inputs	Outputs	Value Added
Mining	Mining companies	Land Mining equipment	Quartzite	Provide essential raw material (quartzite) for silicon production

		Labor		
Materials Processing	Materials Processing plants	Quartzite Energy—electricity Chemical agents	Metal Grade Silicon (MG-Si)	Refine raw quartzite to create a base material for solar-grade silicon production
Silicon Manufacturing	Silicon manufacturers Chemical processing plants Equipment suppliers	MG-Si Chemical agents Energy	Solar Grade Silicon (Poly-Si)	Produce high-purity silicon suitable for solar cells, enhancing energy conversion efficiency
Ingot & Wafer Production	Ingot manufacturers Wafer manufacturers Equipment suppliers (for wafer cutting and fabrication)	Poly-Si Cutting equipment Energy	Ingots and wafers	Prepare silicon in usable wafer form
Solar Cell Manufacturing	Solar cell manufacturers Equipment suppliers (for cell production)	Wafers Conductive materials (silver or aluminum)	Solar cells	Add energy conversion capability by making cells that convert sunlight into electricity.
Solar Panel Assembly	Solar panel manufacturers Component suppliers (for glass, frame and others)	Solar cells Glass Frames Encapsulation materials	Assembled solar panels	Add protection and packaging cells in a durable form ready for electricity generation
Distribution	Logistics and transport companies Warehousing companies	Packaged panels Transport vehicles Warehousing	Solar panels ready for sale and installation	Ensures products reach installation sites safely and efficiently
Installation	Solar developers Installation companies Utility	Panels Tools Labor (installers)	Operational PV systems	Add panels to start generating electricity by connecting them to the grid or batteries

Operation & Maintenance	PV system owners Solar developers O&M service providers	Maintenance equipment Monitoring systems	Optimally and stably functioning PV systems	Ensures long-term efficiency and reliability Maximizes energy production
End of Life	Recycling companies Waste management companies Government agencies Solar developers	Retired panels Recycling facilities	Recycled materials Waste	Reduces environmental impact by recycling materials Managing waste sustainably

Figure 3. Value Chain Map of the PV System

3.1-Study Area

The life cycle stages of photovoltaics involve

(1) Raw material extraction,
(2) Component manufacturing,
(3) Distribution centres and logic,
(4) Installation,
(5) Operation and maintenance,
(6) End-of-life management

This study will answer these questions by analyzing life cycle assessment (LCA). The main role of LCA is to analyze the carbon emissions of PV systems in each life cycle stage. A life cycle assessment (LCA) of PV systems aims to evaluate the environmental impacts of a product, process, or activity (Chau et al., 2015). It involves identifying and measuring the energy and materials used in the manufacturing and production of the PV system, as well as its use and emissions to the environment (Chau et al., 2015). Additionally, it seeks to identify and implement strategies for improving the system's environmental performance (Chau et al., 2015). ISO 14040 and ISO 14044 standards provide the framework for conducting LCA, covering goal definition, inventory analysis, impact assessment, and interpretation. For this study, the focus is on PV systems manufactured in the United States and China, two of the largest global PV markets. The assessment considers regional variations in energy sources, manufacturing practices, and environmental policies to provide a comprehensive analysis of carbon emissions throughout the PV life cycle to identify the difference between China and the US. To provide a visual summary of the life cycle stages analyzed, there is the LCA map of the PV systems, as shown in Figure 4.

Life Cycle Stage	Key Inputs	Key Outputs

Raw Materials	Silicon ore, metals (silver, copper, aluminum), chemicals	Silicon for PV cells, aluminum for frames, glass for panel cover
Manufacturing	Solar cell, aluminum frame, encapsulation layer	Solar panel, emissions from production
Distribution	Assembled solar panels, transport vehicles	Installed solar energy systems, waste from packaging
Usage	Solar panels, mounting systems, inverters, sunlight	Clean electricity, equipment maintenance
End-of-Life	Used solar panels, energy for recycling	Waste products, recovered materials (silicon, glass, aluminum)

Figure 4. Life Cycle Assessment (LCA) of the PV Systems

3.2-Data Collection

Data collection forms the foundation of this LCA, requiring detailed and accurate inputs from all life cycle stages. Primary data sources include national and regional energy grid data for the US and China, which comes from the U.S. Environmental Protection Agency (EPA). To enhance accuracy and reliability, secondary data from lifecycle databases such as Ecoinvent and the China Products Carbon Footprint Factors Database (CPDC) are utilized. Ecoinvent is particularly valuable for its comprehensive datasets covering materials, energy use, and emissions across various industrial processes and global regions. CPDC provides standardized emission factors to manage the carbon footprint of various products, especially in China. Also, the study leverages data from Climate TRACE, a platform that provides detailed, sector-specific carbon emissions data for specific periods and locations. For example, Climate TRACE enables the quantification of carbon emissions from the aluminum industry in the US and China in 2022. So, based on Climate TRACE, it is possible to compare carbon emissions of two locations, such as China and the US, in a specific period and within the same industrial sector, such as primary aluminum production for solar panel frames. This capability ensures the inclusion of accurate, granular data for assessing industry-specific and regional emissions, enhancing the overall robustness of the analysis.

3.3-Analysis Methods

The analysis adopts a cradle-to-grave approach, capturing emissions from raw material extraction to end-of-life management. The process begins with inventory analysis, which quantifies energy consumption, material usage, and emissions for each stage. These data are then used in impact assessment, where carbon footprints are calculated using global warming potential (GWP) factors. Sensitivity analysis is also applied to identify key parameters influencing carbon emissions and to evaluate the uncertainty and variability in results, which can compare variations in the grid, electricity consumed in the installation process, and recycling methods.

3.4-Methods and Models

Let S_t represent the total carbon emissions over the entire life cycle of a photovoltaic (PV) power generation system, measured in kilograms of CO_2 equivalent ($kgCO_2e$). The total emissions can be broken down into emissions from different stages of the life cycle as follows:

$$S_t = S_1 + S_2 + S_3 + S_4 + S_5 + S_6$$

where:

S1: Carbon emissions during the raw material acquisition stage
S2: Carbon emissions during the component manufacturing stage
S3: Carbon emissions during the transportation stage
S4: Carbon emissions during the installation stage
S5: Carbon emissions during the operation and maintenance stage
S6: Carbon emissions during the end-of-life management stage

According to the Center for Sustainable Systems at the University of Michigan (2024), PV modules generally weigh between 34 and 62 lbs (15.4 to 28.1 kg). Assuming the total weight of a PV system module is 20 kg, **Figure 5** illustrates the components, materials, proportions of each part, and the corresponding weight of each component (Ziemińska-Stolarska et al., 2021).

Component	Material	Percentage	Component Weight
Frame	Aluminum	18%	3.6
Cables	Tinned wire (Polymer)	2%	0.4
Surface	Glass	70%	14
Encapsulation layer	EVA, adhesive layer	5%	1
Back-sheet layer	Polyvinyl fluoride	1.5%	0.3
Solar cell	Silicon	4%	0.8
Metallization of modules	Silver	0.05%	0.01

Figure 5. One Module Composition of PV Systems

3.4.1-Raw Material Extraction

The first stage is the material extraction, involving the mining of quartz for silicon production and metals for panel frames. The primary raw materials include aluminum, tinned wire (polymer), tempered glass, EVA (adhesive layer), polyvinyl fluoride, silicon, and silver (Ziemińska-Stolarska et al., 2021). Carbon emissions during the raw material extraction stage primarily result from the energy-intensive processes involved in mining and transporting raw materials, such as silicon, aluminum, and silver, as well as from the initial processing of these materials into industrial inputs. Additional emissions may also arise from waste management and disposal associated with these activities.

The function in this stage is illustrated below:

$$S_1 = \sum_{i}^{n} G_{1i} R_{1i},\ i = 1$$

S_1: The sum of the carbon footprint at this stage in $kgCO_2e$.

R_{1i}: Emission factor for material i^{th} in $kgCO_2e/kg$, $kgCO_2/m^3$, and $kgCO_2e/L$, based on life cycle inventory data obtained from the Ecoinvent Version 3.11 database.

G_{1i}: Total quantity of material of type i^{th} in kg, m^3, and L.

n: Total number of types of materials in this stage.

3.4.2-Component Manufacturing

Subsequent stages focus on material processing, including the conversion of quartz to metallurgical-grade silicon and eventually high-purity solar-grade silicon. The energy-intensive ingot and wafer production processes, which involve melting and slicing silicon, are also included. The manufacturing of solar cells through doping processes and the assembly of solar panels are completed at this stage. Emissions are estimated based on the energy efficiency and mix at manufacturing facilities. Figure 6 provides a visualization of the flow of materials and components in the solar module, i.e., the supply chain map for one solar module.

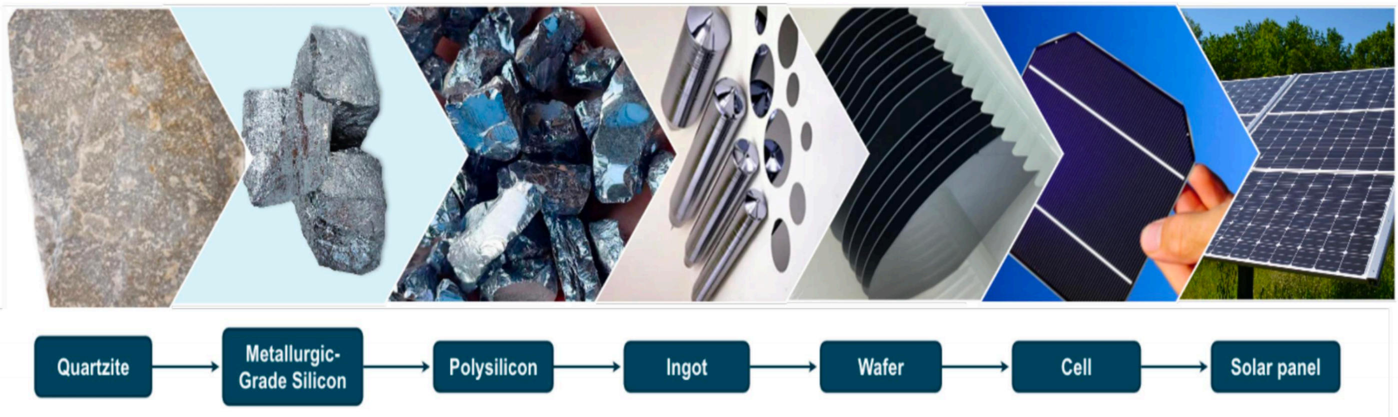

Figure 6. Solar Module Supply Chain Map

The function in this stage is illustrated below:

$$S_2 = \sum_{i}^{n} G_{2i} R_{2i},\ i = 1$$

S_2: The sum of the carbon footprint at this stage in $kgCO_2e$.

R_{2i}: Emission factor for each energy or resource type i (in $kgCO_2e/kg$, $kgCO_2e/kWh$, or $kgCO_2e/GJ$), based on the energy source mix or fuel type, and obtained from Ecoinvent or other relevant databases.

G_{2i}: Consumption of i^{th} energy or resources for gasoline, diesel, water, electricity, and heat in kg, kWh, and GJ.

n: Total number of types of materials in this stage.

3.4.3-Distribution and Logistics

Transportation and logistics represent another critical stage, where emissions are calculated based on transportation modes such as flights, trucks, rail, and ships. Typical transportation-related carbon emissions include emissions from transporting raw materials from production sites to PV module manufacturing facilities, emissions from inter-factory transportation within PV module production enterprises, and emissions from transporting finished products to project installation sites.

The function in this stage is illustrated below:

$$S_3 = \sum_{i}^{n} G_{3i} R_{3k} D_{3i},\ i = 1$$

S_3: The sum of the carbon footprint at this stage in $kgCO_2e$.

R_{3k}: Emission factor for the k^{th} mode of transport in kilograms of CO_2 equivalent per kilometer in $tCO_2e/(t\text{-}km)$, indicating the amount of carbon dioxide equivalent emitted per metric ton of cargo transported one kilometer. Emission factors are based on average values from life cycle databases such as Ecoinvent and depend on the transport mode (e.g., truck, rail, ship).

G_{3i}: Transport weight of material equipment item type i^{th} in kg.

D_{3i}: Transportation distance of material equipment of type i^{th} in km.

n: Total number of types of materials in this stage.

3.4.4-Installation

The carbon emissions during the installation stage primarily include carbon emissions from the production of construction materials, carbon emissions from the use of fuels from equipment during construction and installation, and carbon emissions from electricity consumption during the construction process.

The function in this stage is illustrated below:

$$S_4 = \sum_{i}^{n} G_{4i} R_{4i},\ i = 1$$

S_4: The sum of the carbon footprint at this stage in $kgCO_2e$.

R_{4i}: Emission factor for the ith activity or input during the installation stage,

expressed in appropriate units (e.g., $kgCO_2e/kg$ for construction materials such as concrete and steel, $kgCO_2e/kWh$ for electricity used on-site, $kgCO_2e/L$ or $kgCO_2e/GJ$ for fuel consumption by construction machinery). Emission factors are derived from the Ecoinvent database and account for upstream processes, including fuel production, electricity generation mix, and material manufacturing processes.
G_{4i}: Consumption of the ith type of energy or resource—such as gasoline, diesel, electricity, or water—measured in kg, kWh, or GJ. For water, the upstream emissions associated with its extraction, treatment, and transport are included when applicable. Heat consumption is accounted for through its source energy type, typically either electricity or fossil fuels, to ensure accurate emission attribution.
n: Total number of types of materials in this stage.

3.4.5-Operation & Maintenance

The operation and maintenance stage of a photovoltaic (PV) power generation system is typically characterized by low emissions, as electricity generation itself does not produce direct greenhouse gas emissions. However, emissions do occur during maintenance activities, including the use of gasoline-powered equipment such as zero-turn lawnmowers for vegetation control, as well as occasional transportation to the site for inspection and cleaning. In this study, emissions from routine maintenance-related fuel consumption are acknowledged and incorporated into the analysis. Emissions from the replacement of damaged panels and components, however, are excluded due to their infrequency and limited availability of reliable data.

The function in this stage is illustrated below:

$$S_5 = S_b + S_c + S_d + \sum_{i}^{n} G_{5i} R_{5i},\ i = 1$$

S_5: The sum of the carbon footprint at this stage in $kgCO_2e$.
R_{5i}: Emission factor for material i^{th} in $kgCO_2e/kg$.
G_{5i}: Total quality of consumable item of type i^{th} in kg.
S_b: Carbon emissions from the acquisition of raw materials to replace or upgrade, calculated as S_1 $kgCO_2e$.
S_c: Carbon emissions from the manufacturing process to replace or upgrade, calculated as S_2 in $kgCO_2e$.
S_d: Carbon emissions from transportation to replace or upgrade, calculated as S_3 in $kgCO_2e$.
n: Total number of types of materials in this stage.

3.4.6-End-of-Life Management

The end-of-life management stage of PV systems includes four distinct components:
(1) Disassembly—emissions associated with labor and equipment used to dismantle panels and supporting structures;

(2) Transportation—emissions from transporting dismantled materials to recycling centers, landfills, or treatment facilities;
(3) Waste treatment—emissions resulting from incineration, landfill, or other disposal methods applied to non-recyclable components;
(4) Recycling and reuse—the avoided emissions from material recovery processes, which offset emissions by reducing the need for virgin material production.
The function in this stage is illustrated below:

$$S_6 = \sum_{i}^{n} G_{6i} R_{6i} D_{6i} - \sum_{i}^{n} H_x F_x, \ i = 1, \ x = 1$$

S_6: The sum of the carbon footprint at this stage in $kgCO_2e$.

R_{6i}: Emission factor for material i^{th} in $kgCO_2e/kg$ and $kgCO_2e/kWh$.

G_{6i}: The amount of energy used of each type i^{th} in kg and kWh.

D_{6i}: Transportation distance of material equipment of type i^{th} in km.

H_x: Total quality of the x^{th} recyclable material in kg.

F_x: CO_2 emission factor for x^{th} recyclable material in $kgCO_2e/kg$.

n: Total number of types of energy resources used in this stage.

IV. RESULTS

The results presented are based on the assumption that the mass of a single solar panel is 20 kg, a power density of 200 W/m², and a power-to-weight ratio of 7 W/kg; its area is approximately 0.78 m². Moreover, this result is based on a global geographical scope, not specific to any single country or region. After analyzing the carbon emissions of the life cycle stages of PV modules globally, section 4.7 will continue to compare the situations in the United States and China based on the global results. Transportation was primarily conducted via sea using container ships, which is a common logistical method in the industry but contributes minimally compared to overall emissions among aircraft, trains, lorries, and barges in inland waterways.

In the production of the total output, the carbon emissions in the manufacturing stage are the highest, reaching 476 $kgCO_2e$ per module, representing 88.4% of the total emissions, as shown in **Figure 7**. Specifically, the carbon emissions in the early stage of material preparation account for 38.91 $kgCO_2e$ per module, representing 7.2% of the total; the carbon emissions from the transportation stage are 1.02 $kgCO_2e$ per module, making up 0.19% of the total; the emissions from installation processes are 1.035 $kgCO_2e$ per module, which is 0.19% of the total; the emissions from operation and maintenance processes are 17.15 $kgCO_2e$ per module, which is 3.18% of the total; and the emissions from waste treatment are 4.245 $kgCO_2e$ per module, constituting 0.79% of the total.

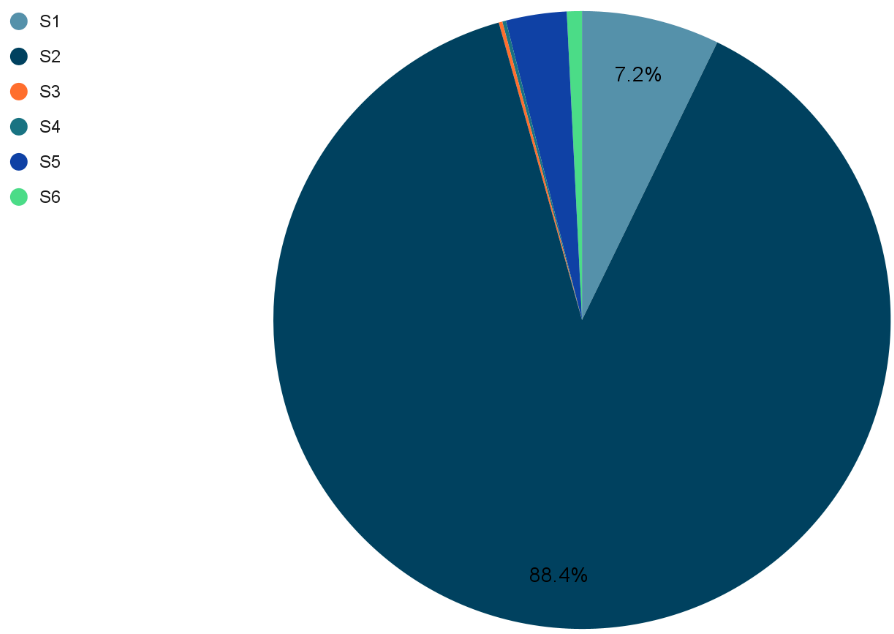

Figure 7. Carbon Footprint of Each Stages in the PV System

Figure 8 reveals the meaning and percentage of six stages from S1 to S6 in the worldwide.

Stage	Description	Emissions ($kgCO_2e$/module)	Percentage of Total (%)
S1	Raw Material Preparation	38.91	7.22
S2	Manufacturing	622.94	88.42
S3	Transportation	1.02	0.19
S4	Installation	1.034	0.19
S5	Operation & Maintenance	17.15	3.18
S6	Waste Treatment	4.25	0.79

Figure 8. Carbon Footprint Distribution Across Life Cycle Stages of a PV System

4.1-Raw Material Extraction

At this stage, aluminum contributes the most significant CO_2 emissions among the materials listed, with 38.907 $kgCO_2e$ per module, which represents a substantial 7.22% of the total emissions for this component. This high value is predominantly due to its energy-intensive smelting process.

In contrast, despite glass accounting for a substantial portion of the total weight, other materials like tinned wire (polymer) and tempered glass contribute relatively low emissions, amounting to 0.304 $kgCO_2e$ and 2.44 $kgCO_2e$ per module, respectively. These figures are considerably less impactful, constituting only 0.78% and 6.26% of the total emissions for the respective materials. The results underscore the significant variability in carbon footprint across different materials used in solar panel production, highlighting the importance of targeting specific high-impact areas like aluminum processing for emissions reduction initiatives.

4.2-Component Manufacturing

In the manufacturing phase, substantial carbon emissions are generated, emphasizing its significant environmental impact within the solar panel production lifecycle. The data indicates that silicon manufacturing alone contributes a striking 102.696 $kgCO_2e$ per module. This stage is particularly impactful due to the intensive energy requirements and chemical processes involved in refining and preparing silicon for photovoltaic cells. The energy consumed during the manufacturing of metallurgical-grade silicon and subsequent processing steps like silicon crystal growth and wafer production are major contributors.

Additionally, the production of ingots and wafers is another high-emission activity, resulting in 193 $kgCO_2e$ per module. These processes involve melting and crystallizing silicon, which are energy-intensive and result in significant CO_2 emissions. This phase's high emissions are a direct consequence of the substantial amount of electricity derived from carbon-intensive sources, highlighting the need for renewable energy integration in manufacturing processes to significantly reduce the carbon footprint of solar panel production.

4.3-Distribution and Logistics

In this section, we assume the distance for transporting solar panels is 5000 km. In the analysis of transportation modalities for distributing solar panels across a distance of 5000 kilometers, different methods were scrutinized for their environmental impact, particularly focusing on carbon emissions per module. Rail transportation emerged as the most carbon-efficient, with emissions of 5.19 $kgCO_2e$ per module, attributed to the high efficiency and lower friction associated with freight trains. Maritime transport via container ships also showed low emissions at 1.02 $kgCO_2e$ per module, making it a suitable option for long-distance, high-volume transportation due to its capacity to move large quantities efficiently across continents.

Conversely, road and air transport demonstrated higher carbon footprints. Road transport through unspecified lorries resulted in 16.1 $kgCO_2e$ per module, while air freight was the least environmentally sustainable option, emitting 84 $kgCO_2e$ per module, largely due to the high energy requirements and carbon intensity of aviation fuels. Inland waterway transport using diesel-powered barges offered a moderate emission level of 5.23 $kgCO_2e$ per module, serving as a viable alternative in certain geographic conditions. These findings emphasize the need for strategic logistic planning and the adoption of more sustainable transportation methods to align solar panel distribution with global sustainability goals, reducing the overall environmental impact of renewable energy technologies.

4.4-Installation

The installation phase has little impact on the overall carbon footprint of the PV system. Emissions arise primarily from the use of handheld electric tools (e.g., screwdrivers, drills) and are often below 1.1 $kgCO_2e$ per module. Given the minor impact, the primary focus for emissions reduction remains in the distribution and logistics stage.

4.5-Operation & Maintenance

During the operation and maintenance phase of solar farms, the routine activities assume no replacements of parts due to damage to the solar panels themselves. Instead, one significant maintenance activity is vegetation management using heavy-duty equipment to ensure optimal panel exposure to sunlight. A key piece of equipment utilized in this process is a large diesel-powered mower, with an assumed operational time of 50 hours annually for regular maintenance across the solar farm. In contrast, rooftop solar installations typically do not require vegetation control, resulting in even lower maintenance-related emissions. As such, the operation and maintenance footprint for rooftop PV systems is generally negligible compared to utility-scale ground-mounted systems.

The vegetation management at solar farms is typically carried out using diesel-powered, heavy-duty mowing equipment, such as a tractor with a bush hog attachment, designed for clearing dense vegetation efficiently across large areas. This analysis models the mower as a standard agricultural tractor operating at an average speed of 15 km/h during mowing. Unlike freight vehicles, this equipment does not carry payloads, so the concepts of “loaded” and “empty” are not applicable here.

Based on equipment specifications and fuel efficiency data, the mower is estimated to consume approximately 1 MJ of diesel energy per minute of operation, equivalent to about 0.0222 kg of diesel per minute. Given the maintenance schedule of 50 operating hours per year, this results in a total consumption of 4,000 MJ of diesel annually for mowing activities. The associated carbon emissions are calculated using standard emission factors for diesel combustion, accounting for upstream fuel production and on-site use.

Transportation within the site primarily involves the use of lorries to move solar panels and equipment around the solar farm. This internal logistics ensures the effective distribution and positioning of panels or necessary maintenance equipment across extensive areas of the farm. Therefore, at this stage, the total emission is the sum of the operation of the diesel-powered mower and the lorries transportation, which is 17.15 $kgCO_2e$.

4.6-End-of-Life Management

In the end-of-life management phase of solar panel systems, the transportation component plays a crucial role, primarily involving the movement of decommissioned panels to designated recycling facilities or landfill sites. This transport is predominantly conducted via lorries, which are used to haul the panels over considerable distances, such as 500 km, ensuring they reach the appropriate processing centers. Key activities include recycling and landfilling, with a focus on minimizing the environmental impact associated with disposal. The model data highlights two primary materials involved in recycling: tempered glass and aluminum. Tempered glass, constituting 79.55% of the module's recyclable content, is treated through glass recycling processes that effectively reduce its environmental footprint by utilizing it in various applications, resulting in a CO_2 emissions impact of 0.18 $kgCO_2e$ per module. Aluminum, making up 20.45% of the recyclable material, undergoes treatment through municipal incineration and sanitary landfill processes. This aluminum recycling results in a CO_2 emissions saving, significantly lowering the module's overall emissions by 0.042 $kgCO_2e$.

Furthermore, the landfilling component primarily deals with inert materials that do not decompose or release harmful gases. The inert material used in this context is accounted for at 2.4 kg per module, emphasizing a minimal impact scenario where the landfilling process adheres to stringent environmental management practices to ensure low emissions, marked by a factor for energy-related CO_2 emissions, making it a lower-impact disposal method for non-recyclable components when managed under strict environmental controls. This end-of-life strategy effectively aligns with environmental sustainability goals, aiming to maximize recycling and minimize the ecological footprint of decommissioned solar panels.

4.7-Comparative Analysis Between US and China

This comparative analysis mainly focuses on the raw material extraction and component manufacturing stages, since these two stages account for over 90% of the total carbon footprint in the life cycle stages.

4.7.1-Comparative Analysis at the Raw Material Extraction

This section presents a comparative analysis of material production at the raw material extraction stage and associated emissions for key components utilized in photovoltaic (PV) systems within the US and China. **Figure 9** includes three main components of one PV module: aluminum, glass, and silicon, since they account for about 92% of the total weight. Therefore, these three components have a decisive influence on the entire manufacturing stage of the PV systems.

Material	Production in China (tons)	Production in US (tons)	Emission Quantity of China (tCO_2e)	Emission Quantity of US (tCO_2e)	Emission per Module in China (tCO_2e)	Emission per Module in USA (tCO_2e)
Aluminum	45,845,073	826,733	255,151,118.3	4,212,264.47	5.66	5.1
Glass (tempered)	45,021,647	40,500,000	2,155,850.54	9,312,025.97	0.048	0.23
Silicon	4,700,250	345,023	163.57	12.01	0.0000348	0.0000348

Figure 9: Production and Emissions of Key PV Materials in the US and China

For the production volume, China dominates in the production of aluminum and glass, key components for PV systems, highlighting its role as a major player in the global PV market. The production of aluminum and glass in China far exceeds that in the US, which is consistent with the country's expansive manufacturing capacity and vertically integrated supply chains.

For the general emission impacts, the emission levels linked to production are much greater in China for all examined elements. For instance, emissions from aluminum production in China are over 60 times more than those in the United States, highlighting the environmental impact of coal-dependent energy in Chinese industry.

Despite the increased overall emissions, the emissions per module for materials like glass are somewhat lower in China compared to the US. This may be ascribed to more efficient large-scale industrial methods in China, which, although still significantly polluting, advantageously leverage economies of scale.

4.7.2-Comparative Analysis at the Component Manufacturing

At the component manufacturing stage, emissions per module in China are 490 $kgCO_2e$, while emissions per module in the US are 476 $kgCO_2e$ (China Products Carbon Footprint Factors Database, 2020). The emissions linked to the production of a single photovoltaic module are somewhat more in China than in the USA. The disparity is 14 $kgCO_2e$ per module, indicating that manufacturing processes in China may be less carbon-efficient or dependent on more carbon-intensive energy sources than those in the USA.

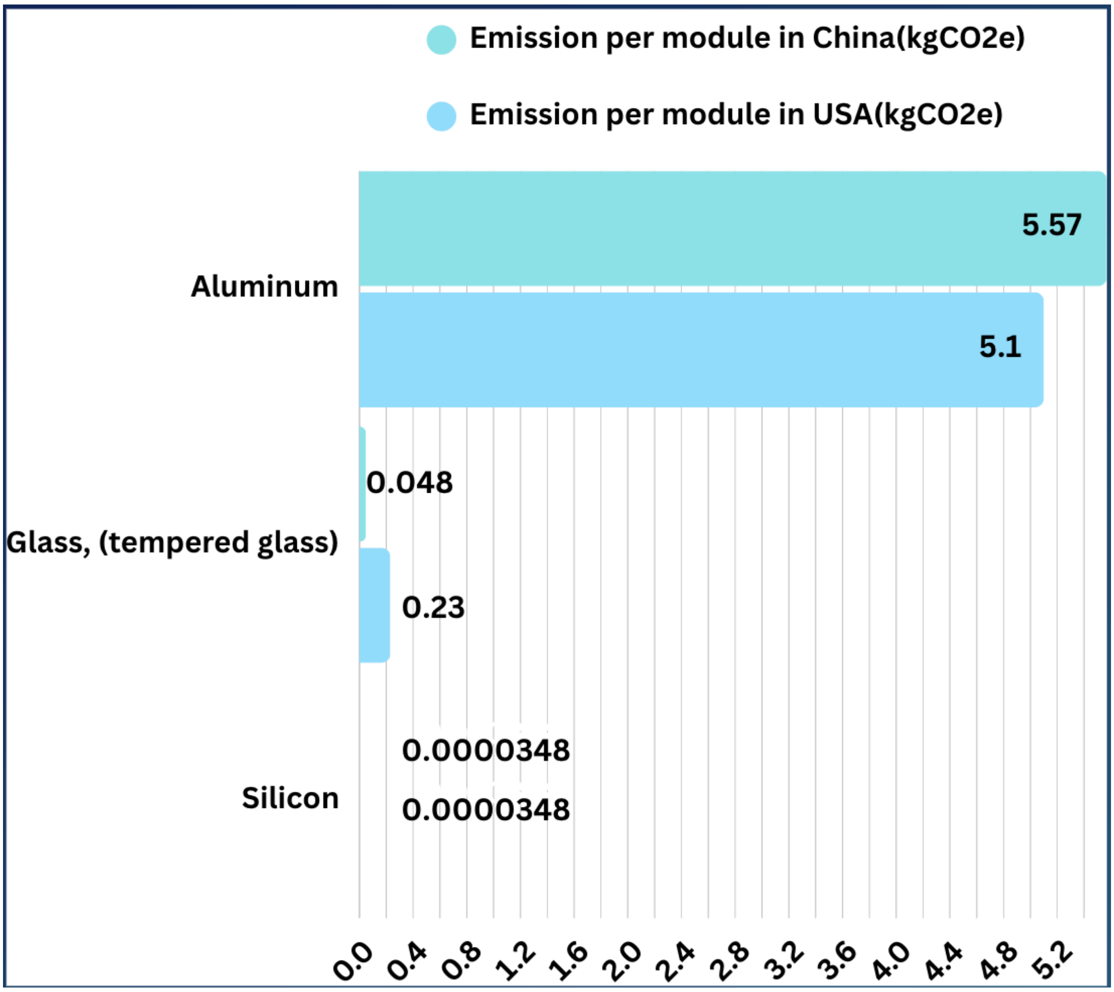

Figure 10: Comparison Between US and China in the Raw Material Stage

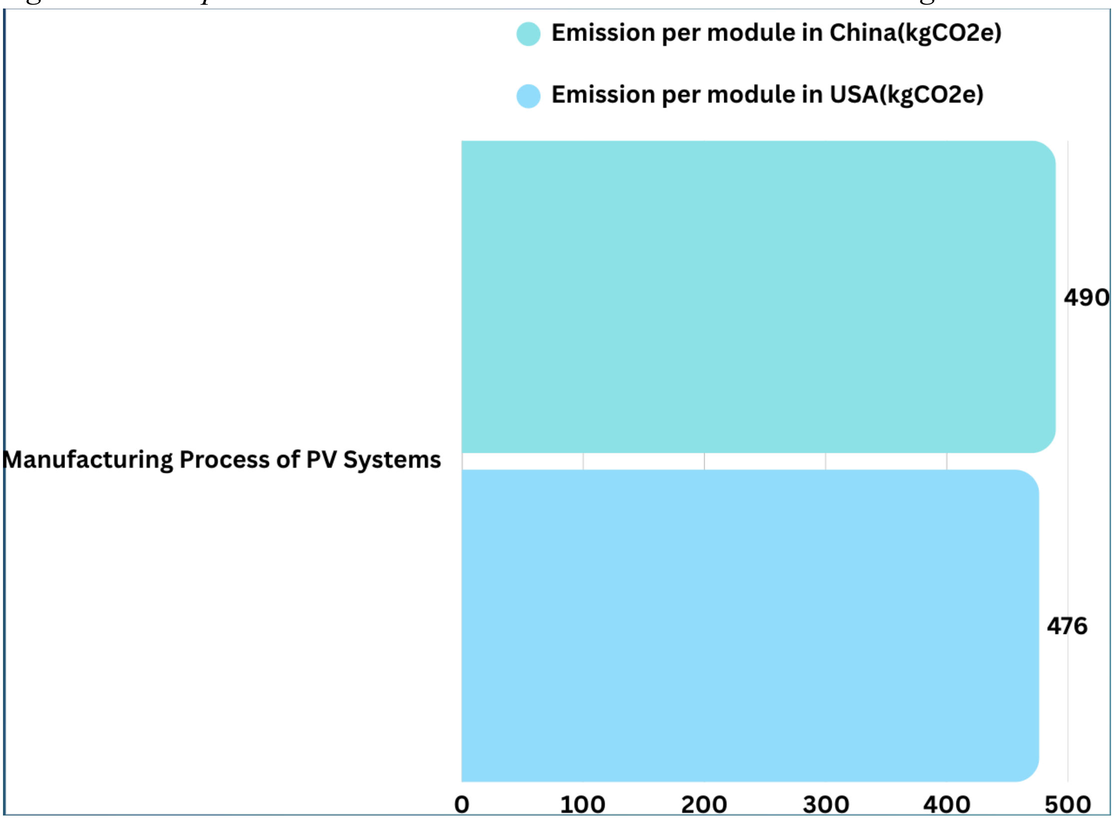

Figure 11: Comparison Between US and China in the Manufacturing Stage

IV. DISCUSSION

A PV system manufactured in China is associated with approximately 490 kg of CO_2-equivalent emissions over its life cycle. Using the greenhouse gas equivalencies calculator from EPA, this amount of greenhouse gas emissions is roughly equivalent to driving 1,248 miles in an average gasoline-powered passenger vehicle, burning 544 pounds of coal, or consuming 55.1 gallons of gasoline (Greenhouse Gas Equivalencies Calculator | US EPA, 2025). It also equals the emissions from using 41.4 gallons of diesel fuel and would take about 8.1 tree seedlings growing for ten years to offset (Greenhouse Gas Equivalencies Calculator | US EPA, 2025). These comparisons help contextualize the environmental impact of PV manufacturing and underscore the importance of decarbonizing the production phase.

4.1-Limitations

This study, while comprehensive, has several limitations that could impact the generalizability and accuracy of the results. One significant limitation is the variability in data quality across different sources and regions, which might have introduced inconsistencies in the life cycle assessment (LCA). Furthermore, the comparative study's focus on just two countries—China and the US—limits its applicability to other regions where manufacturing practices, energy sources, and environmental regulations may differ significantly. Additionally, there is a lack of detailed and standardized data, particularly in the production and manufacturing phases, where variations in material sourcing, factory efficiencies, and supply chain logistics can significantly influence carbon footprint calculations. These gaps in data availability and consistency could lead to uncertainties in the overall assessment and highlight the need for more comprehensive, region-specific studies.

4.2-Recommendations for Future Analysis

Future studies could expand the geographical scope to include more countries with significant PV production, providing a more global perspective on the carbon footprint of PV systems. Additionally, incorporating primary data collection could enhance the accuracy of the LCA. Researchers should also explore the impact of emerging technologies in PV manufacturing and recycling, which could significantly alter the environmental profiles of solar panels. Further analysis could also examine the socio-economic impacts of large-scale PV adoption, including job creation and energy security, to provide a more holistic view of sustainability in the solar industry.

V. CONCLUSION

This study has assessed the lifecycle carbon emissions of photovoltaic (PV) systems, highlighting the critical stages that significantly contribute to the environmental footprint of solar panels. Throughout the analysis, it became evident that the manufacturing stage is the most carbon-intensive, primarily due to the energy requirements and processes involved in producing raw materials like silicon and aluminum. Efforts to minimize these emissions are crucial for enhancing the sustainability profile of solar technology.

The findings also underscored the complexities of managing end-of-life PV modules, where practices such as recycling and proper waste management are vital yet challenging due to technological and logistical constraints. Furthermore, the transportation and installation phases, though less impactful per unit compared to manufacturing, still contribute significantly when scaled to global deployment levels. Optimizing these aspects through better logistics, local manufacturing, and the use of environmentally friendly transport options can further reduce the carbon footprint.

In conclusion, while solar energy remains a cornerstone for clean energy transition, enhancing its sustainability through comprehensive lifecycle management is imperative. This study provides a foundation for future research and development focused on reducing the environmental impact of solar panels, thereby supporting the global shift towards a more sustainable and low-carbon future. Future studies should expand to more geographical areas and incorporate emerging technologies to provide a broader and more detailed perspective on the lifecycle impacts of solar energy systems.

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