6TH International Conference and Workshop on Engineering and Technology Research (ICWETR) LAUFET 2025: 234-249

Assessment of the Energy Payback Period and Life Cycle Carbon Footprint of a 12 W Rooftop Polycrystalline Solar Photovoltaic Module

[1]Olatide O. S., [2]Adewumi V. A., [3]Oluwadare M. O., [4]Alagbe-Shehu S. and [5*]Sangotayo E. O.

[1,2,3,4,5]*Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria,*

https://www.laujet.com/

Keywords:

Photovoltaic Module,
Energy,
Payback,
Carbon Footprint,
Global Warming

Corresponding Author:
eosangotayo@lautech.edu.ng

ABSTRACT

The adoption of small-scale solar photovoltaic (PV) systems is crucial for promoting sustainable energy solutions, particularly in off-grid applications. This research paper investigated the life cycle carbon footprint and energy payback period of a 12W polycrystalline solar PV module, utilizing the life cycle impact assessment (LCIA) methodology executed via OpenLCA software. The study used environmental indicators governing equations such as Cumulative Energy Demand (CED), Energy Payback Time (EPBT), Global Warming Potential (GWP), Greenhouse Gas Payback Time (GHG-PBT), greenhouse gas emission rate, CO_2 emission rate, and CO_2 payback time, offering insights into the environmental performance of this compact solar technology. The system boundary considered includes the pre-manufacturing and manufacturing phases in China, along with transportation logistics in both Nigeria and China. The installation, operational, and end-of-life disposal stages were conducted in Ogbomoso, with the assessment based on an average global horizontal irradiance of 4.846 kWh/m² per day. The results revealed a total CED of 1232 MJ for the entire life cycle, which translates to 15,400 MJ/m², with 63% attributed to polysilicon processing and the ingot and wafer-making stages. The calculated EPBT is 16.12 years, while the primary energy production is estimated at 76.4117 MJ/year. The net energy benefit (NEB) over the module's 30-year lifetime was 1060.35 MJ. The study showed that a GWP of 136 kg CO_2-eq for the module's entire life cycle. The GHG-PBT is calculated at 11.72 years using Nigeria's grid emission factor of 0.547 kg CO_2/kWh, with the GHG emission rate identified as 0.214 kg CO_2-eq/kWh. The CO_2 emission rate is determined to be 0.203 kg CO_2 per kWh, leading to a CO_2 payback time of 14.15 years. This research presented the viability of 12 W polycrystalline solar PV modules as sustainable energy solutions in off-grid contexts. Future research directions may involve optimizing manufacturing processes and enhancing the overall sustainability of solar PV systems to further reduce their environmental impact

INTRODUCTION

The extensive application of solar photovoltaic (PV) systems as a sustainable substitute for fossil fuels has been driven by the rising need for renewable energy. Polycrystalline silicon solar modules are a favored option among many photovoltaic technologies owing to their comparatively high efficiency and cost-effectiveness. Nonetheless, solar photovoltaic (PV) systems are not entirely free from carbon emissions, despite their ecological benefits. The carbon footprint of photovoltaic modules throughout their life cycle is affected by manufacturing, transportation, installation, and disposal procedures (Kim and Fthenakis 2006). This footprint should be assessed to determine its genuine sustainability. Life Cycle Assessment (LCA) is a critical tool for evaluating the total environmental impact of a product, encompassing the extraction of raw materials through to its disposal after its lifecycle. The life cycle carbon footprint measures the greenhouse gas (GHG) emissions linked to each phase of the solar photovoltaic module's life cycle. Understanding this footprint is essential for improving manufacturing processes, optimizing energy efficiency, and reducing the overall environmental impact of solar technology (Peng *et al.*2013).

The Energy Payback Period (EPP) is an essential statistic in evaluating sustainability to measure the duration required for a solar module to provide an equivalent amount of energy to that which it expended during its entire life cycle. A reduced EPP signifies a more energy-efficient technology, hence diminishing the environmental impact. The EPP is affected by factors like module efficiency, geographic location, solar irradiation, and balance-of-system (BOS) components for small-scale rooftop photovoltaic modules, such as a 12W polycrystalline panel (Nishimura *et al.* 2010). The sustainability of solar energy systems can be enhanced by finding potential for improvement in photovoltaic module manufacturing, deployment, and recycling through the examination of these parameters. The need for energy has surged due to the exponential growth of the world population and the rapid advancement of economies, leading to an intensified reliance on traditional fossil fuels. The widespread utilization of fossil fuels may lead to numerous significant environmental problems, such as acid rain, global warming, and air pollution, therefore individuals have sought alternative sustainable and renewable energy technologies, especially photovoltaic (PV), to tackle the issues of energy constraints and environmental pollution (Fraas and Partain, 2010).

Solar power refers to the transformation of sunshine into electricity, achieved either via direct photovoltaic (PV) methods or indirect concentrated solar power (CSP). Photovoltaic technology generates electric current by utilizing the photovoltaic effect (Peng and Lu 2013). In principle, solar energy is ecologically advantageous as it does not involve fossil fuel consumption or greenhouse gas emissions during its operation. Nonetheless, the comprehensive life cycle assessment, which includes the fabrication of solar cells, the assembly of photovoltaic modules, the production of a Balance of Systems (BOS), the transportation of materials, the installation and retrofitting of photovoltaic systems, and the disposal or recycling of these systems, necessitates a significant energy input. Thus, Life Cycle Assessment (LCA) is often utilized to scientifically evaluate the overall environmental impact of a Photovoltaic (PV) system installation, as indicated by the commonly used energy payback time (EPBT) metric (Peng *et al*. 2013). LCA is generally characterized as the compilation and assessment of the inputs, outputs, and possible environmental effects of a product system across its life cycle This concept highlights the thorough assessment of environmental impact, which includes the complete input and output processes throughout all phases of a product's life cycle (ISO 14042 and 14043, 2000E). The Life Cycle Assessment (LCA) approach generally comprises four principal components: inventory analysis, specification of objectives and scope, impact assessment, and interpretation, as depicted in Figure 1.

Many studies have explored the environmental impacts of PV systems using life cycle assessment (LCA) methodologies, but several research gaps exist as presented, Fu *et al.* (2015) conducted a thorough life cycle assessment (LCA) of Mc-Si PV systems, emphasizing the substantial contributions of production processes to a variety of environmental impacts, such as acidification, GWP, and human toxicity, with a maximum EPBT of six years. The assessment of the life cycle impact was restricted by the exclusion of the end-of-life phase, which was due to a lack of data on disposal practices in China. Hou *et al*. (2016) presented an investigation into the environmental effects of C-Si PV systems. The findings indicated that manufacturing was responsible for over 84% of energy consumption and GHG emissions, with an EPBT ranging from 1.6 to 2.3 years.

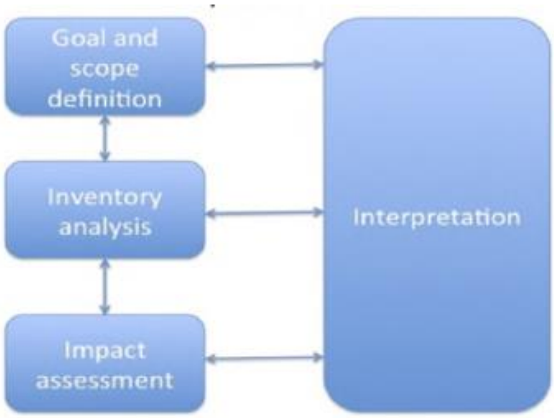

Figure 1: Framework of Life Cycle Assessment

Akinyele *et al*. (2017) conducted a life cycle assessment of a 1.5 kW PV system in Nigeria, observing that regional solar radiation influenced variations in emission rates and energy metrics. The findings are limited by geographical diversity, which may not accurately reflect the effects of PV systems in a variety of environmental conditions.

Huang *et al*. (2017) assessed the environmental impacts of mc-PV systems in China and concluded that recycling resulted in less severe consequences than landfill disposal, despite the difficulties associated with module dismantling and treatment processes. Transportation and usage phases were excluded, which restricted the environmental impact assessment's comprehensiveness. The environmental impacts of mc-si PV modules in China were analyzed by Yang *et al.* (2015) and the study revealed that domestic production has substantial GWP hotspots, while imported Mc-Si has lower emissions. Mohr *et al*. (2012) described that flexible roof-integrated amorphous/nanocrystalline silicon solar laminates exhibit lower material and energy demands during production compared to traditional rigid PV systems. These systems also reduce greenhouse gas emissions while offering seamless integration into building structures. The study did not evaluate the performance and durability of these laminates under varying climatic conditions or consider the end-of-life phase, including recycling and material recovery processes. Giacchetta *et al*. (2013) illustrated that the recovery of valuable materials and the substantial reduction of environmental impacts associated with waste disposal can be achieved through high-value recycling procedures for thin-film photovoltaic modules. This method also reduced the overall carbon footprint of thin-film PV systems.

Lunardi *et al*. (2018) presented a comparison of standalone silicon modules, chalcogenide/si tandem solar modules exhibit improved efficiency and reduced environmental impacts, particularly in terms of energy return time and greenhouse gas emissions. The study did not examine the environmental trade-offs associated with the production of tandem modules at scale or the recycling potential of chalcogenide materials. Rajput *et al*. (2018) showed that the 3.2 kW CDTE's photovoltaic system in India's composite climate offers significant environmental benefits, particularly in terms of energy payback time and reduced greenhouse gas emissions, when compared to conventional energy sources. The system's environmental impacts are predominantly concentrated in the manufacturing stage. The study did not provide insights into the end-of-life phase of the CTDE's system, including recycling potential and material recovery. Sangotayo *et al*. (2018) examined the thermal effect of photovoltaic hybrid solar cells on the electrical efficiency of a solar inverter. The experimental setup included a 150W module, 1000W inverter, 2000 Ah battery, charge controller, solarimeter, environmental recorder, ammeter, and temperature recorder. The results showed a direct relationship between solar radiation, temperature, and output voltage. However, when the ambient temperature rises above 30°C, the output voltage falls. The photovoltaic modules have an exergy efficiency of 49.30%, but electrical efficiency reduces as solar radiation and temperature increase.

Espinosa *et al*. (2011) analyzed flexible polymer solar cells with efficiencies of 2% and 3%, yielding EPBTs of 2.02 and 1.35 years and CO_2 emissions of 56.65 and 37.77 g CO_2eq/kWh, respectively. The primary energy contributor was the ITO on the PET substrate, accounting for 87% of total PE consumption. The EPBT was considerably reduced by the increased efficiency and active area, while the erf was improved. Recycling, end-of-life (EoL) scenarios, and balance of system (BOS) considerations were omitted from the study, which restricted its assessment of the entire life cycle. Parisi *et al*. (2013) assessed dye-sensitized solar cells (DSSCS) from a life cycle perspective, emphasizing their potential as a renewable energy technology with decreased environmental impacts compared to conventional photovoltaics. The significance of material selection and process optimization in minimizing the energy and environmental expenses associated with DSSCS is underscored by the analysis. The evaluation did not investigate the recycling potential of DSSC materials or provide end-of-life (EoL) treatment strategies.

Tsang *et al*. (2016) emphasized that organic photovoltaic (OPV) panels have lower material and energy requirements than conventional PV technologies, which presents a substantial opportunity to mitigate environmental impacts. The advantages of OPV in terms of reduced greenhouse gas emissions and energy utilization during production are emphasized by the cradle-to-grave assessment. The analysis failed to provide a comprehensive examination of the end-of-life (EoL) management and recycling processes for OPV panels. Celik *et al*. (2016) discovered that PSC structures had an EPBT of 1–1.5 years and a GWP of 100–150 g CO_2eq/kWh, with electricity use accounting for up to 90% of the impacts. In comparison to other perovskite methods, Htl-free PSC devices demonstrated reduced environmental impacts. The accuracy of environmental impact estimates was restricted by the absence of comprehensive data on large-scale production processes for perovskite solar cells in the study. Additionally, recycling strategies and end-of-life (EoL) scenarios for PSC structures were not examined. Zhang *et al.* (2017) compared various perovskite solar cell systems, finding that system design and material choices significantly influenced environmental impacts. Devices with reduced lead content and improved energy efficiencies showed lower environmental footprints. The study did not conduct an assessment of recyclability and end-of-life management.

Lunardi *et al*. (2017) conducted an LCA of silicon-based tandem solar photovoltaics, revealing that these systems have lower environmental impacts than conventional silicon-only modules. The end-of-life phase, notably recycling, plays a crucial role in minimizing overall impacts. The study did not thoroughly assess the economic viability of recycling processes. Additional research is required to assess the scalability and real-world efficacy of tandem systems on a commercial scale. Maranghi *et al*. (2019) emphasized the potential of perovskite photovoltaic fabrication to reduce environmental impacts in comparison to silicon-based systems by harmonizing

LCA studies. The environmental profile demonstrated that the primary factors contributing to the impacts of perovskite PVs were energy consumption during production and material use. The literature review indicated there is need to assess the energy payback period and life cycle carbon footprint of a 12 W rooftop polycrystalline solar photovoltaic module.

METHODOLOGY

This methodology section describes the 12W solar PV module environmental impact evaluation strategy.

Life Cycle Impact Assessment (LCIA)

LCIA evaluated a product system's environmental and health implications from resource extraction to material production, manufacturing, usage, and disposal. ISO/TC 207/SC 5 (2006a, b) described LCIA as data compilation and calculation for input, output, and environmental impacts. This study was analyzed using OpenLCA and the module's cradle-to-grave life cycle, from raw material extraction to end-of-life disposal.

System boundary

The PV module system boundaries include pre-manufacturing, production, transportation, installation, usage, and disposal as presented in Figure 2. Before manufacture, raw materials like quartz sand and graphite for silicon PV are extracted, processed, and purified. Manufacturing includes polycrystalline silicon PV module production. The 12W PV module is transported by sea and land from the manufacturing location to the installation site. The PV module generates electricity and is maintained at Ogbomoso during its use. End-of-life disposal of polycrystalline silicon PV modules is also kept in Ogbomoso.

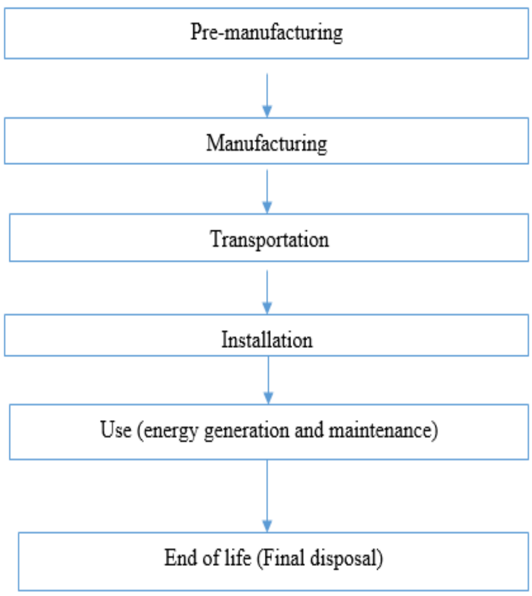

Figure 2: Life cycle stages of a solar PV module

Material description

The following product information, as described by the supplier on the package, was selected from a provision store in the Under-G area of Ogbomoso, Oyo state: a 12W polycrystalline solar panel with 6mm cable and installation clips; integrated with a control unit including a 6.4V, 6Ah battery, and 3 dimmable LED lights. Solar inputs are 9V DC and 1.33A

Outputs are 6.4V DC, 2A max; includes 5 barrel jack ports and 2 USB ports.

The area in m^2 of the PV module was calculated as shown in equation (1)

$$\text{Area} = \text{Power} \div (\text{Efficiency} \times \text{Irradiance}) \quad (1)$$

$$= 12W \div (0.15 \times 1000W/m^2) = 0.08m^2$$

Environmental Indicators

The following indicators were chosen to investigate the environmental aspects of the PV module: Cumulative Energy Demanded (CED), Energy Payback Time (EPBT), CO_2 emission rate, CO_2 payback time (CO_2PBT), Global Warming Potential (GWP), Greenhouse Gas (GHG) emission rate, and the module's impact on human health.

Cumulative Energy Demanded (CED)

CED is the major energy used in a product's life cycle, from pre-manufacturing to waste disposal. Energy is used throughout the solar PV module manufacturing process, from premanufacturing, fabrication, transportation, installation, operation, and disposal. CED was determined using equation (2)

$$\text{CED} = \sum E_i \quad (2)$$

where E_i is the energy required for each life cycle stage

Energy payback time (EPBT)

EPBT is the time needed to recoup a system or product's primary energy consumption from its energy output over its life cycle. Both the main energy demand and annual power generation are included. Eq. (2) calculates a system's EPBT (year) by comparing its total primary energy requirement over its life cycle to its annual electricity generation. Equations. (2) and (3) determined the Energy payback time and Net energy gain, respectively

$$\text{Energy payback time (EPBT, year)} = E_{requirement} \div E_{annual\ generation} \quad (3)$$

$E_{requirement}$ is the system's lifetime primary energy need (MJ) and $E_{annual\ generation}$ is the module's annual primary energy (MJ/year).

$$\text{Net energy gain} = (E_{annual\ generation} \times \text{The lifetime of the PV system}) - E_{requirement.} \quad (4)$$

Global warming potential (GWP)

Greenhouse gases (GHGs) such as CO_2, CH_4, N_2O, HFCs, and SF_6 absorb infrared radiation from the Earth's surface, hence accelerating global warming. GHGs raise global temperatures, leading to climate change, natural disasters, infectious diseases, and ecosystem disruption (Houghton *et al*. 1997). GHG emissions were converted to CO_2 equivalents for global warming equivalent. GWP data were used as gCO_2 equivalent/functional unit to quantify the effects of GHGs on global warming.

Greenhouse Gas (GHG) emission rate

The GHG emission rate is determined using equation (5)

$$\text{GHG emission rate } (gCO_{2eq}/kWh) = LCCO_{2\ equivalent} \div (\text{AEO} \times \text{module's lifetime}) \quad (5)$$

$LCCO_{2\ equivalent}$ is the total $CO_{2\ equivalent}$ emission of the module's life cycle and AEO is the annual energy output or energy yielded in the primary energy equivalent (kWh/year)

CO_2 Payback Time (CO_2PBT)

The number of years needed for a system's CO_2 emissions to be offset by its CO_2 reductions is called CO_2PBT. For CO_2PBT, the system's CO_2 emissions have been estimated, and the polycrystalline silicon PV system's annual CO_2 reduction is calculated by multiplying its kWh output by the Nigerian grid mix's GWPs. This study calculated the net CO_2 reduction from a PV system using equation (6)

$$CO_2 \text{ payback time } (CO_2PBT) = CO_{2\ \text{total emissions}} \div CO_{2\ \text{annual reduction}} \quad (6)$$

The module's $CO_{2\ \text{total emissions}}$ (gCO_2 equivalent) are the entire CO_2 emissions throughout its lifecycle and the $CO_{2\ \text{annual reduction}}$ is the annual CO_2 reduction achieved through the implementation of the system (gCO_2 equiv/year).

Assumptions

The values of certain parameters were established in this study based on assumptions. The locations of various stages in the lifecycle were assumed to be in China, except the use stage and the EoL stage, which are located in the Global Solar Atlas report an average global horizontal irradiance of 4.846 kWh/m^2 per day. This assumption was made due to the absence of a solar PV module manufacturing facility in Nigeria. In addition, the module's efficacy, lifetime, solar irradiance (the quantity of solar radiation that falls on a surface per unit area), and performance ratio (rooftop mounted) were assumed to be 15%, 30 years, 1000 W/m^2, and 0.75, respectively.

Function, functional unit, and reference flow

The module's role was electricity generation and functional units measured product system performance for reference. Table 1 shows the IEA methodology guideline for PV system LCA, which recommends defining the functional unit (F.U.) as 1 kWh of energy generated from the PV module (Anctil *et al*., 2010). The 12W PV module established the reference flow, or PV module size needed to generate 1 kWh. Table 1 depicts function, functional unit, and reference flow.

Table 1: Function, functional unit, and reference flow.

Function	Electricity generation
Functional unit	1 kWh of electricity generated
Reference flow (kg/kWh)	0.0227 kg/kWh

Life Cycle Inventory Analysis

Data Collection and Sources

The inputs and outputs at every stage in the 12W PV module's life cycle were quantified using a life cycle inventory (LCI) study. Data mostly from life cycle inventory databases including the Ecoinvent database (Version 3.7) and the Swiss Centre for Life Cycle Inventories, as data from peer-reviewed studies, Industry reports, the National Renewable Energy Laboratory (NREL), International Energy Agency (IEA), and books on LCA were used and the PV module was modeled.

Pre-manufacturing and manufacturing stages

After mining silica, an arc furnace will convert quartz sand silica to metallurgical-grade silicon (MG-Si) for polycrystalline silicon (mc-Si) PV module manufacture (Koroneos *et al*., 2006). After that, the Siemens technique will purify MG-Si to Poly-Si using hydrogen, hydrochloric acid, and a lot of energy. The mc-Si ingot will be formed by melting and casting Poly-Si into big blocks, which does not require the high, sustained temperatures needed for single-crystal silicon (sc-Si) manufacture (Tao, 2008). mc-Si ingots are sliced into wafers with thicknesses based on PV module capacity and size. These wafers would undergo cell-production procedures. To maximize light absorption, these wafers will be textured and etched. After that, an emitter layer will establish the p-n junction needed to generate electricity, and a rear surface will boost conductivity with contact. Tao (2008) suggested applying an antireflective coating to reduce reflection and increase light absorption. Cells will be laminated with glass, EVA, and a rear foil after preparation. Heating the assembly to melt the EVA will encapsulate it, making it durable. The photovoltaic effect created power from the PV module after aluminum framing and cable connections were added. Raw quartz sand was transformed into a fully built polycrystalline photovoltaic module that harnesses solar energy.

Transportation stage

The module's transportation stage from the factory in China to Ogbomoso, where it was installed, was modeled with the presumed distance as follows, as the module is assumed to be manufactured in China: sea transportation from China to Lagos, Nigeria: 20,325 km and road transportation from Lagos to Ibadan to Ogbomoso, Under G: 237.7 km via Google Map.

Installation

The solar module was installed on the rooftop of the provision store by a solar technician with an average weight of 66 kg within the range of 30 to 35 minutes, with a height ranging from 2.5 to 3.0 meters.

Use stage

It is essential to calculate the total electricity generated from the PV module. For the analysis of the use stage, the nominal power of the 12 W polycrystalline silicon PV module is 12 W. Using the given solar irradiation of 4.846 kWh/m²/day,

The daily energy output was calculated using equation (7)

$$\text{Daily energy output} = \text{Efficiency} \times \text{Average GHI} \times \text{Area} \tag{7}$$

$$= 0.15 \times 4.846\,\text{kWh/m}^2\text{/day} \times 0.08\ \text{m}^2 = 0.058152\ \text{kWh/day}$$

$$\text{Annual Energy Output} = \text{Daily energy output} \times 365\text{days}$$

$$= 0.058152 \times 365 = 21.22548\ \text{kWh/year}$$

$$\text{Actual total energy output for 30 years} = \text{Annual energy Output} \times 30\ \text{years}$$

$$= 21.22548\ \text{kWh/year} \times 30\ \text{years}$$

$E_{total} = 636.7644$ kWh

1 kWh = 3.6 MJ

636.7644 kWh × 3.6 MJ/kWh

E_{total}= 2292.35184 MJ

Also, the major maintenance carried out throughout this stage is the cleaning of the dust accumulated on the surface of the solar module during the dry seasons to ensure that the module's surface is exposed to the solar radiation properly.

End of life stage

The end-of-life stage of the PV module will be the activities involved in decommissioning and disposing of the PV module which is entirely the landfill process. The data requirement at the end-of-life stage will be the energy input and the emission (CO_2 and other emissions) generated during the decommissioning and disposal of the PV module. The OpenLCA software calculated the impact scores for the chosen indicators in each life cycle stage using a variety of LCIA methods, including the CED method, the IPCC (Intergovernmental Panel on Climate Change) method, the IMPACT 2002+ method, the ReCiPe method, and the CML method. This investigation is aimed at assessing the life cycle carbon footprint and environmental product profile (EPP) of a 12W rooftop polycrystalline solar photovoltaic module,

RESULT AND DISCUSSIONS

The findings of the LCA effect of the 12W polycrystalline solar photovoltaic module are presented and discussed in this section.

Cumulative Energy Demand (CED)

Figure 3 presents the variation of energy demand (MJ per module) against the life cycle stage. The Cumulative Energy Demand (CED) for the 12W polycrystalline silicon photovoltaic module in this study was calculated to be 1232 MJ over its full life cycle. The most energy-intensive phases were polysilicon processing (500 MJ), ingot, and wafer production (450 MJ total), which together constituted 60.23% of the overall energy requirement. These procedures entail energy-intensive activities, including the production of metallurgical-grade silicon (MG-Si), purification via the Siemens process, and wafer slicing, all of which are documented as important contributors to the energy consumption of photovoltaic modules. The CED per unit area was determined to be 15,400 MJ/m², which is considerably elevated because of the limited module area (0.08 m²) and the substantial energy requirements for silicon purification and wafer manufacturing. Although transportation (15 MJ, 1.22%) and end-of-life disposal (10 MJ, 0.81%) contributed minimally to the overall cumulative energy demand (CED), localized production and enhanced recycling technologies could potentially diminish the energy profile of photovoltaic (PV) systems.

The implementation of renewable energy in photovoltaic manufacturing facilities has been shown to decrease cumulative energy demand by as much as 30% (Kim *et al.,* 2014), while enhanced recycling and localized production will further diminish energy consumption associated with transportation. This study establishes that the purification of silicon and wafer processing are the most energy-intensive phases in photovoltaic manufacture, necessitating efficiency enhancements. Enhanced production methodologies, recycling initiatives, and localized manufacturing can substantially reduce sustainability impacts while further decreasing the overall energy requirements of polycrystalline photovoltaic modules.

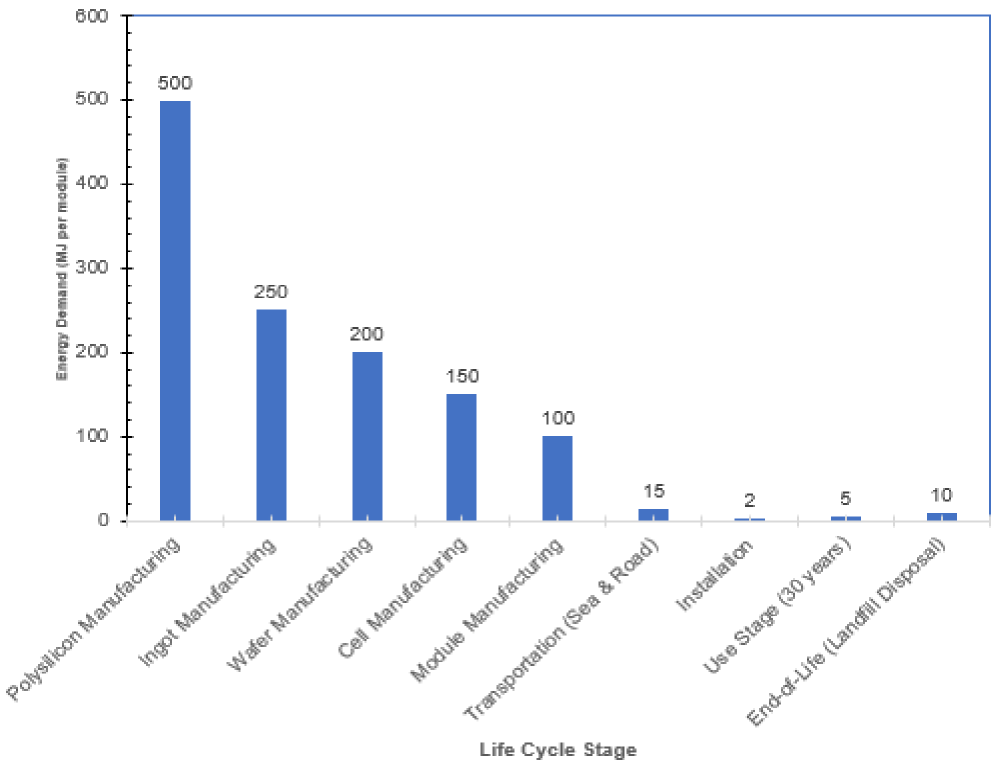

Figure 3 Plot of Energy Demand (MJ per module) against Life Cycle Stage

The Energy Payback Period (EPBP)

Figure 4 presents the energy payback time and net energy benefit of the 12W polycrystalline PV module. The Energy Payback Time (EPBT) for the 12W polycrystalline silicon solar module is 16.12 years, representing the duration necessary to produce energy equivalent to its Cumulative Energy Demand (CED) of 1232 MJ.

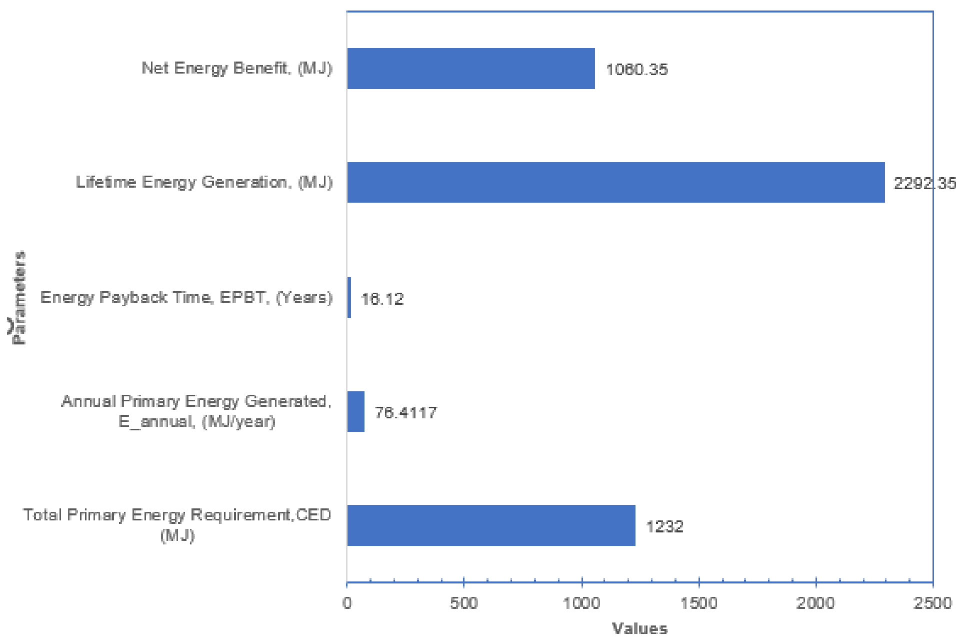

Figure 4 Energy Payback Time and Net Energy Benefit of the 12W Polycrystalline PV Module

The module produces 76.4117 MJ of primary energy annually, resulting in a Net Energy Benefit (NEB) of 1060.35 MJ throughout its 30-year lifespan, signifying that it generates 1.86 times the initial energy investment. The elevated EPBT is mostly attributable to energy-intensive production processes, especially polysilicon purification and wafer fabrication, which require substantial energy consumption. Despite the extended energy payback period, the module maintains a net positive energy yield, further reinforcing its viability as a sustainable energy solution. The EPBT obtained was 16.12-year substantially exceeding those reported for contemporary PV modules. Literature references indicate a lifespan of 2.5 to 4 years for first-generation multicrystalline silicon modules (Alsema and de Wild-Scholten, 2007) and 1.5 to 4 years contingent upon solar conditions (Peng *et al*., 2013). Subsequent advancements in technology yield published numbers of 1–2.5 years for contemporary polycrystalline modules, as reported by Frischknecht *et al*. (2020), indicating enhancements in efficiency and wafer thinning. Additional studies on commercial photovoltaic systems reveal significantly reduced energy payback times (EPBT) of 0.5–2 years for high-efficiency monocrystalline and perovskite-based modules (Fthenakis *et al*., 2008; Tao *et al*., 2008). The elevated EPBT in this study is mostly attributable to the diminutive module size (12W), middling efficiency (15%), and substantial embodied energy during production. To boost its energy payback, measures such as increased efficiency (>18%), silicon recycling, streamlined production, and improved transport logistics must be used to align with global trends in photovoltaic sustainability.

Global Warming Potential (GWP)

The Global Warming Potential (GWP) of the 12W polycrystalline silicon photovoltaic (PV) module examined in this study is 136 kg CO_2-equivalent over its full life cycle, as shown in Figure 5. Greenhouse gas emissions per functional unit (1 kWh of electricity generated) amount to 0.214 kg CO_2-equivalent per kWh, calculated by dividing the total greenhouse gas emissions by the total energy output of 636.7644 kWh as shown in Figure 5.

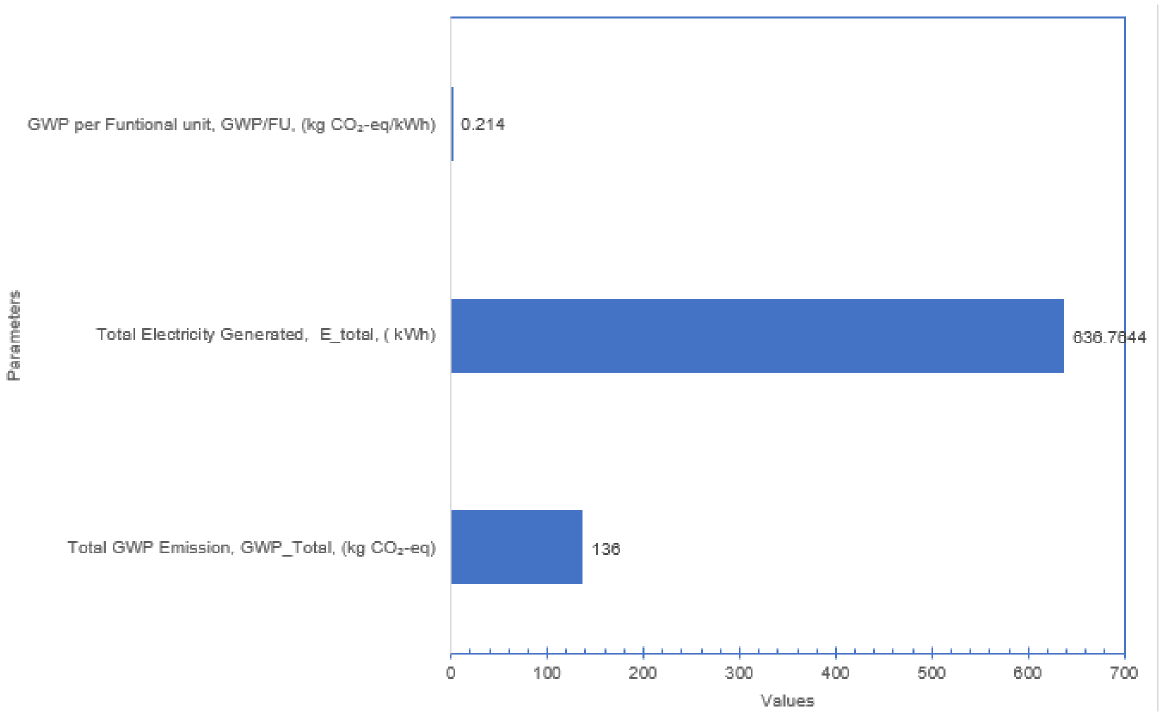

Figure 5: Global Warming Potential per Functional Unit of the 12W Polycrystalline PV Module

The primary sources of these emissions are the production processes, including polysilicon refining, wafer-cell fabrication, and module assembly, which collectively account for a substantial amount of emissions. Transportation, installation, and end-of-life disposal provide relatively minor yet significant additions to the overall footprint. Notwithstanding these emissions, the module is a more environmentally friendly source than power generated from fossil fuels. Former studies estimated greenhouse gas emissions for commercial multi-crystalline silicon photovoltaic modules at 0.02–0.1 kg CO_2-equivalent per kilowatt-hour, but high-efficiency monocrystalline and thin-film photovoltaic systems exhibit significantly lower emissions, ranging from 0.01 to 0.06 kg CO_2-equivalent per kilowatt-hour (Frischknecht *et al.*, 2020). The increased emissions in this study stem from low module efficiency (15%), limited scale (12W), and energy-intensive production procedures. To diminish the GHG footprint, measures such as enhancing efficiency (>18%), augmenting recycling processes, employing renewable energy for manufacturing, and optimizing logistics must be executed to align with worldwide trends in PV technology.

The Greenhouse Gas Payback Period (GHG PBP)

The Greenhouse Gas Payback Time (GHG PBT) for the 12W polycrystalline silicon photovoltaic module is 11.72 years, indicating that it will require almost 12 years to offset the 136 kg CO_2-equivalent emissions generated throughout its lifespan. The calculation employs Nigeria's grid emission factor of 0.547 kg CO_2/kWh, representing the carbon intensity of grid power. The module's yearly energy production of 21.22548 kWh prevents the emission of 11.61 kg CO_2-eq annually from fossil fuel combustion, hence reducing reliance on fossil fuel-derived electricity. Despite its relatively noteworthy greenhouse gas production before tax, the module nonetheless achieves net carbon emission reduction during its full 30-year lifespan, so it qualifies as a renewable energy source. Compared to existing literature, this GHG PBT of 11.72 years is markedly greater than the values reported for contemporary PV installations. Research has shown that the greenhouse gas payback time (GHG PBT) for multicrystalline silicon modules generally falls between 1.5 and 5 years (Frischknecht *et al.*, 2020), while thin-film photovoltaics exhibit substantially shorter payback durations. The extended GHG PBT in this study is mostly attributable to low module efficiency (15%), diminutive system size (12W), and energy-intensive manufacturing processes. To enhance GHG payback performance, it is essential to deploy better efficiency modules (>18%), improved recycling methods, and manufacturing powered by renewable energy, while closely adhering to global sustainability standards.

Greenhouse Gas (GHG) Emission Rate

The GHG emission rate for the 12W polycrystalline silicon PV module is 0.214 kg CO_2-eq per kWh, derived from a total life cycle GHG emission of 136 kg CO_2-eq and a total lifetime energy output of 636.7644 kWh over 30 years, as presented in Figure 6. The value prioritizes the module's carbon footprint, which is influenced by energy-intensive production processes (polysilicon purification and cell-wafer fabrication), transit from China to Ogbomoso, and the average solar irradiation (4.846 kWh/m^2/day). Moreover, the module presents a more environmentally friendly option compared to Nigeria's grid electricity, which has an average emission factor of 0.547 kg CO_2-eq/kWh (IEA, 2019). This is a 61% decrease in greenhouse gas emissions per unit of power produced by the photovoltaic module, in comparison to grid electricity, thereby categorizing it as a comparatively lower-carbon energy source.

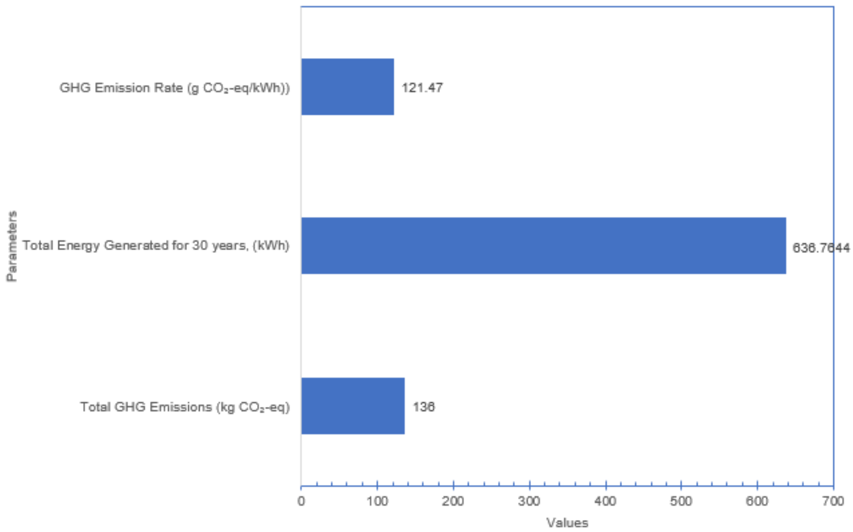

Figure 6 The GHG Emission Rate

This study's emission factor of 0.214 kg CO_2-eq/kWh exceeds that of most current polycrystalline silicon PV systems, which typically range from 0.02 to 0.12 kg CO_2-eq/kWh (Fthenakis *et al*., 2008; Frischknecht *et al*., 2020). Peng *et al*. (2013) reported that Chinese photovoltaic systems produce between 0.05 and 0.18 kg CO_2-equivalent per kilowatt-hour. The elevated emissions are attributable to the minuscule 12W module size, comparatively low efficiency (15%), and production reliant on fossil fuels. To enhance environmental performance, the implementation of high-efficiency modules (>18%), optimization of energy sources in the manufacturing process (e.g., solar or hydroelectric), and the promotion of material recycling are essential measures to mitigate the carbon footprint of small-scale photovoltaic systems.

CONCLUSIONS

The assessment of the energy payback period (EPP) and life cycle carbon footprint of a 12W rooftop polycrystalline solar photovoltaic module provides important insights into its environmental sustainability. The study emphasized that solar photovoltaic (PV) systems reduce greenhouse gas emissions during operation; yet, their environmental footprint is considerably influenced by the energy-intensive manufacturing processes, shipping, and disposal at the end of their lifecycle. The life cycle carbon footprint analysis indicates that the balance-of-system (BOS) components, module manufacture, and silicon purification are the primary sources of emissions. The predicted EPP suggested that the module can recoup its embodied energy in a relatively short timeframe, depending on the local solar irradiance levels. Polycrystalline photovoltaic (PV) technology offers a good energy return on investment and meaningfully lowers long-term carbon emissions compared to traditional fossil fuel-based energy sources. It is essential to emphasize the optimization of material recycling to enhance the sustainability of solar PV modules, the integration of cleaner energy sources, the prolongation of module lifespan, and the enhancement of energy efficiency in production. Future developments in photovoltaic technology and recycling tactics might further diminish the carbon footprint and enhance the energy payback period, making solar energy an increasingly sustainable answer for global energy needs.

REFERENCES

Akinyele, D. O., Rayudu, R. K., and Nair, N. K. C. (2017). Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria. *Renewable Energy, 101*, 537–549. https://doi.org/10.1016/j.renene.2016.09.018

Anctil, A., and Fthenakis, V. (2012). Life cycle assessment of organic photovoltaics. In *Third Generation Photovoltaics* (pp. 91–110).

Anctil, A., Babbitt, C., Landi, B., and Raffaelle, R. P. (2010). Life-cycle assessment of organic solar cell technologies. In *Proceedings of the 2010 35th IEEE Photovoltaic Specialists Conference* (pp. 742–747), Honolulu, HI, USA, June 20–25. https://doi.org/10.1109/PVSC.2010.5616889

Espinoza, J.C., Fraizy, P., Guyot, J.-L., Ordo˜nez, J., Pombosa, R., and Ronchail, J. (2011). La variability des debits du Rio Amazonas au P´erou. Climate Variability and Change-Hydrological Impacts. IAHS Publ, 308:424429.

Fraas L. and Partain L.(2010) Solar Cells and their Applications Second Edition, Wiley, , ISBN 978-0-470-44633-1,

Fthenakis V M, Kim H C, Alsema E, (2008) Emissions from photovoltaic life cycles, Journal of Environmental Science and Technology, 42(6): 2168-74.

Fu, Y., Liu, X., and Yuan, Z. (2015). Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. *Journal of Cleaner Production, 86*, 180–190. https://doi.org/10.1016/j.jclepro.2014.08.061

Frischknecht, Rolf and Stolz, Philippe and Krebs, Luana and de Wild-Scholten, Mariska and Sinha, Parikhit. (2020). Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems 2020 Task 12 PV Sustainability. 10.13140/RG.2.2.17977.19041.

Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y., and Yao, Q. (2016). Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. *Applied Energy, 164*, 882–890. https://doi.org/10.1016/j.apenergy.2015.11.058

Huang, B., Zhao, J., Chai, J., Xue, B., Zhao, F., and Wang, X. (2017). Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. *Solar Energy, 143*, 132–141. https://doi.org/10.1016/j.solener.2017.09.014

International Energy Agency (IEA). (2019). *Global energy and CO_2 status report: The latest trends in energy and emissions in 2018*. Retrieved from https://iea.blob.core.windows.net/assets/23f9eb39-7493-4722-aced-61433cbffe10/Global_Energy_and_CO2_Status_Report_2018.pdf

International Energy Agency. (2019). *Renewables 2019: Market analysis and forecast from 2019 to 2024*. IEA.

ISO International Standard 14042, (2000E). Environmental management - Life cycle assessment - Life cycle Impact assessment. International Organisation for Standardisation (ISO), Geneva.

ISO International Standard 14043, (2000E). Environmental management - Life cycle assessment - Life cycle Interpretation. International Organisation for Standardisation (ISO), Geneva.

Kim, B. J., Lee, J. Y., Kim, K. H., and Hur, T. (2014). Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. *Solar Energy, 99*, 100–114. https://doi.org/10.1016/j.solener.2013.10.036

Kim, H. C., and Fthenakis, V. M. (2011). Comparative life-cycle energy payback analysis of multi-junction International Energy Agency. (2019). *Renewables 2019: Market analysis and forecast from 2019 to 2024*. IEA.

Koroneos, C., *et al*. (2006). Life cycle assessment of silicon-based photovoltaics. *Renewable Energy, 31*(13), 1822-1838. https://doi.org/10.1016/j.renene.2005.08.016

Lunardi, M. M., Moore, S., Alvarez-Gaitan, J. P., Yan, C., Hao, X., and Corkish, R. (2018). A comparative life cycle assessment of chalcogenide/Si tandem solar modules. *Energy, 145*, 700–709. https://doi.org/10.1016/j.energy.2017.12.125

Lunardi, M. M., Wing, Y., Ho-Baillie, A., Alvarez-Gaitan, J. P., Moore, S., and Corkish, R. (2017). A life cycle assessment of perovskite/silicon tandem solar cells. *Progress in Photovoltaics: Research and Applications, 25*(8), 679–695. https://doi.org/10.1002/pip.2893

Maranghi, S., Parisi, M. L., Basosi, R., and Sinicropi, A. (2019). Environmental profile of the manufacturing process of perovskite photovoltaics: Harmonization of life cycle assessment studies. *Energies, 12*(19), 3746. https://doi.org/10.3390/en12193746

Mohr, N. J., Maijer, A., Huijbregts, M. A. J., and Reijnders, L. (2012). Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. *Progress in Photovoltaics: Research and Applications, 21*(4), 802–815. https://doi.org/10.1002/pip.2216

Nishimura A, Hayashi Y, Tanaka K, Hirota M, Kato S, Ito M, (2010). Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Applied Energy;87:2797–807.

Parisi, M. L., Maranghi, S., Sinicropi, A., and Basosi, R. (2013). Development of dye-sensitized solar cells: A life cycle perspective for the environmental and market potential assessment of a renewable energy technology. *International Journal of Heat and Technology, 31*(1), 143–148. https://doi.org/10.18280/ijht.310120

Peng J., and Lu L. (2013) Investigation on the development potential of rooftop PV systems in Hong Kong and its environmental benefits. Renewable and Sustainable Energy Reviews; 27: 149-162.

Peng J., Lu L. and Yang H., (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of a solar photovoltaic system. *Renewable and Sustainable Energy Reviews*;19:255-74.

Tao, M. (2008). Inorganic photovoltaic solar cells: Silicon and beyond. In A. Barnett and C. Honsberg (Eds.), *Inorganic Photovoltaic Solar Cells* (pp. 1-18). Elsevier.

Tsang, M. P., Sonnemann, G. W., and Bassani, D. M. (2016). Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Solar Energy Materials and Solar Cells, 156*, 37–48. https://doi.org/10.1016/j.solmat.2016.02.023

Yang, D., Liu, J., Yang, J., and Ding, N. (2015). Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade. *Journal of Cleaner Production, 94*, 35–45. https://doi.org/10.1016/j.jclepro.2015.01.045

Sangotayo, E. O., Itabiyi, O. E., Mudashiru, L. O., Adeyemo, T. Oyeniran, N. D, Jalekun, O. I, (2018). Thermal Effect of Photovoltaic Hybrid Solar Cells on Electrical Efficiency of Solar Inverter, Adeleke University Journal of Engineering and Technology [AUJET] 1(1), pp.184-195

Zhang, J., Gao, X., Deng, Y., Zha, Y., and Yuan, C. (2017). Comparison of life cycle environmental impacts of different perovskite solar cell systems. *Solar Energy Materials and Solar Cells, 166*, 9–17. https://doi.org/10.1016/j.solmat.2017.03.002.