

Assessment of Energy Payback and Life Cycle Carbon Emissions for a 12 W Rooftop PV module

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Abstract: The advancement of sustainable energy solutions, particularly in off-grid contexts, is contingent upon the implementation of small-scale solar photovoltaic (PV) systems. Employing the life cycle impact assessment (LCIA) methodology implemented through OpenLCA software, this study report investigated the energy return period and life cycle carbon footprint of a 12W polycrystalline solar photovoltaic module. The study utilized environmental indicators, such as cumulative energy demand (CED), energy payback time (EPBT), global warming potential (GWP), greenhouse gas payback time (GHG-PBT), greenhouse gas emission rate, CO₂ emission rate, and CO₂ payback time, to offer a comprehensive understanding of the environmental performance of this compact solar technology. The pre-production and manufacturing stages in China, as well as transportation logistics in Nigeria and China, are all included in the defined system boundaries. The evaluation was based on an average global horizontal irradiance of 4.846 kWh/m² per day, and the installation, operating, and end-of-life disposal phases took place in Ogbomosho.

The results showed a cumulative CED of 1232 MJ for the entire life cycle, which is equivalent to 15,400 MJ/m². Polysilicon processing and the ingot and wafer fabrication phases were attributed to 63% of the total CED. The principal energy output is estimated at 76.4117 MJ per annum, and the Energy Payback Time (EPBT) is 16.12 years. Throughout the module's 30-year lifecycle, the net energy benefit (NEB) was 1060.35 MJ. According to the analysis, the module's entire life cycle has a global warming potential (GWP) of 136 kg CO₂ -eq, which equates to 0.214 kg CO₂ -eq/kWh. Utilizing Nigeria's grid emission factor of 0.547 kg CO₂ /kWh, the GHG emission rate is established at 0.214 kg CO₂ -eq/kWh, and the GHG-PBT is determined to be 11.72 years. The CO₂ emission rate is 0.203 kg CO₂ per kWh, which leads to a CO₂ repayment period of 14.15 years.

This study illustrated the viability of 12 W polycrystalline solar photovoltaic modules as sustainable energy solutions in off-grid environments. In order to further reduce the environmental impact of solar photovoltaic systems, future research may concentrate on optimizing manufacturing processes and enhancing their sustainability.

Key-Words: - Photovoltaic Module, Energy, Payback, Carbon Footprint, Global Warming

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1. Introduction

It is essential to assess the environmental and economic viability of a 12 W rooftop photovoltaic (PV) module by analyzing its energy return and life cycle carbon emissions. This involves evaluating the complete lifecycle of the photovoltaic module, encompassing manufacture and decommissioning, to ascertain the energy payback time (EPBT) and carbon footprint. The carbon emissions assessment quantifies the greenhouse gases released during the

lifecycle, while the EPBT measures the duration required for a photovoltaic system to yield an equivalent amount of energy to that expended in its production. These criteria are essential for evaluating the environmental effect and sustainability of photovoltaic systems, especially as they gain prevalence in residential and commercial applications.

The Energy Payback Time (EPBT) for photovoltaic systems depends on the technology employed and

the geographic area. For instance, thin film photovoltaic systems have an energy payback time (EPBT) ranging from 0.75 to 3.5 years, whereas mono-crystalline silicon (mono-Si) systems demonstrate an EPBT between 1.7 and 2.7 years (Peng et al., 2013). In Brazil, a 1.2 kWp rooftop system utilizing monocrystalline panels has an energy payback time (EPBT) of 2.47 to 3.13 years (Fukurozaki et al., 2013). With an irradiation of 1700 kWh/m²/yr, rooftop systems often exhibit an EPBT of 2.5 to 3 years (Alsema, 2000). Photovoltaic systems exhibit significantly reduced carbon emissions compared to fossil fuel-based electricity, with thin film systems generating between 10.5 and 50 g CO₂-eq/kWh (Peng et al., 2013). At now, rooftop systems generate 50–60 g CO₂/kWh, with the possibility of reducing emissions to 20–30 g CO₂/kWh in the future (Alsema, 2000). CO₂ emissions for a rooftop system in Brazil vary from 14.54 to 18.68 g CO₂-eq/kWh (Fukurozaki et al., 2013).

Sumper et al. (2011) examined the energy return time and greenhouse gas emissions of photovoltaic systems in the context of the life-cycle assessment (LCA). Despite the fact that it does not explicitly address a 12 W rooftop PV module, it underscores the significance of evaluating energy payback and emissions across a variety of PV technologies. The problem statement underscores the necessity of thorough assessments of the environmental consequences of solar energy technologies during the manufacturing and installation phases, as they are essential for comprehending the overall sustainability of these technologies. Rachoutis and Koubogiannis (2016) evaluated the Energy Payback Time (EPBT) and Life Cycle Carbon Emissions (LCCE) of rooftop photovoltaic (PV) systems in Greece, underscoring the significance of renewable energy in the attainment of Nearly Zero Energy Buildings (NZEB). To effectively inform sustainable building practices and energy conservation measures, the problem statement emphasizes the necessity of comparing the embodied energy and CO₂ emissions of PV systems to their energy production, particularly for a 12 W module.

Zhai and Williams (2010) conducted a life cycle assessment (LCA) of photovoltaic systems with a particular focus on the analysis of embodied energy

and carbon emissions. The problem statement underscores the importance of evaluating the energy payback time (EPBT) and life cycle carbon emissions of a 12 W rooftop PV module, particularly in light of the significant energy consumption and emissions that occur during the manufacturing, installation, and decommissioning phases. In order to assess the environmental and sustainability implications of rooftop solar technologies in the context of the increasing adoption of PV, it is essential to understand these metrics. Fthenakis and Alsema (2006) assessed the energy payback periods and life cycle carbon emissions of a variety of PV technologies. Under typical Southern European conditions, the study determined that the energy payback periods ranged from 1.7 to 2.7 years and the GHG emissions ranged from 21 to 45 g CO₂-eq/kWh.

Zhai and Williams (2010) concentrated on multicrystalline silicon photovoltaic (PV) systems, citing an energy payback time (EPBT) of 2.2 years and a decrease in embodied carbon emissions from 60 g CO₂/kWh in 2001 to 21 g CO₂/kWh in 2011, which underscored technological advancements. Sumper et al. (2011) conducted a life-cycle assessment of a 200 kW rooftop PV system, which highlighted the substantial environmental impact during the manufacturing and installation phases of PV modules. The study detailed the energy payback time of 4.36 years and greenhouse gas emissions. Ding et al. (2023) did not conduct a specific evaluation of the energy return or life cycle carbon emissions for a 12 W rooftop PV module. It concentrated on the comprehensive carbon emissions associated with PV production, which encompasses lifecycle analysis, manufacturing innovations, and end-of-life management strategies. The lifecycle assessment of solar PV systems was presented by Karduri and Ananth in 2024. This assessment evaluated the energy inputs and carbon emissions from manufacturing to recycling. Nevertheless, it does not explicitly address the energy return or carbon emissions for a 12 W rooftop PV module. Using the life cycle assessment methodology, Fukurozaki et al. (2013) evaluated the energy payback time (EPBT) and CO₂ emissions of a 1.2 kWp rooftop PV system in Brazil. They

determined that the EPBT ranged from 2.47 to 3.13 years and the CO₂ emissions were 14.54 to 18.68 g CO₂ eq/kWh.

Peng et al. (2013) conducted a review of life cycle assessments (LCA) of a variety of photovoltaic (PV) systems, emphasizing the significance of energy return time (EPBT) and greenhouse gas (GHG) emissions. A detailed evaluation of a 12 W rooftop PV module can offer valuable information regarding its environmental impact and sustainability. The challenge is in comprehending the energy return and carbon emissions of this module in comparison to established PV technologies, which is essential for the effective decision-making process of sustainable energy solutions in residential applications. Alsema (2000) evaluated the energy pay-back time (EPBT) and CO₂ emissions of photovoltaic (PV) systems, with an emphasis on the energy requirements for manufacturing. The challenge is in assessing the sustainability of a 12 W rooftop PV module, as current research indicates substantial discrepancies in energy inputs and emissions. Understanding these metrics is essential for assessing the long-term feasibility of PV technology in reducing CO₂ emissions and addressing global warming, thereby informing future developments in PV production technology.

Fukurozaki et al. (2013) were concerned with the evaluation of the energy payback time (EPBT) and life cycle carbon emissions of a 1.2 kWp photovoltaic (PV) rooftop system in Brazil. The problem statement underscores the necessity of assessing the environmental consequences of PV systems, particularly in relation to energy inputs and CO₂ emissions, to advance sustainable energy solutions. It is essential to comprehend these metrics to inform policy decisions and promote the adoption of renewable energy technologies in residential settings. The life-cycle impacts of silicon-based PV modules were assessed by Kato et al. (1998), with a particular emphasis on energy return time (EPBT) and life-cycle CO₂ emissions. The issue at hand is the increasing environmental concerns surrounding PV systems, which require a comprehensive evaluation of their sustainability. The study emphasized the necessity of examining the energy

recovery and carbon emissions of a 12W rooftop PV module in the context of current and near-future technologies to guarantee their effective integration into residential energy solutions.

The thermal effects of photovoltaic (PV) hybrid solar cells on the electrical efficiency of a solar inverter are the subject of an experimental study by Sangotayo et al. (2018). The system comprises a 150 W PV module, a 1000 W inverter, a 2000 Ah battery, a charge controller, a solarimeter, an environmental recorder, an ammeter, and a 12-channel temperature recorder. The study examined the impact of weather on thermal performance by employing thermodynamic principles of energy and exergy balance under steady-state conditions. The findings indicate that solar radiation, temperature, and voltage are inextricably linked; however, voltage output decreases when the ambient temperature surpasses 30°C. The PV module attained an exergy efficiency of 49.30% at a temperature of 27–31 °C and a wind speed of 0–0.2 m/s. However, the electrical and exergy efficiencies were 5.86% and 42.61%, separately. PV optimization is guided by the fact that efficiency decreases as temperature increases.

Borisov et al. (2025) conducted a review of the life cycle of photovoltaic (PV) plants, with a particular emphasis on the time required for energy return and carbon emissions. The evaluation of a 12 W rooftop PV module entails the comparison of the energy input during manufacturing, installation, and operation with the energy produced over the module's lifecycle. Quantifying the carbon footprint associated with each life cycle stage, identifying inefficiencies, and investigating improvements to enhance sustainability and reduce environmental impact are critical for advancing solar energy's role in the green transition. There are still obstacles to surmount to further reduce energy return times and carbon emissions, despite the fact that the current assessments suggest promising results for the sustainability of PV systems. Improvements in manufacturing technologies and lifecycle management are required to improve the environmental performance of PV modules (Borisov et al., 2025).

2. Methodology

The environmental impact evaluation strategy for the 12W solar PV module is explained in this methodology section.

2.1 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.

2.2 System boundary

The PV module system boundaries include pre-manufacturing, production, transportation, installation, usage, and disposal as presented in Fig. 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 Ogbomosho during its use. End-of-life disposal of polycrystalline silicon PV modules is also kept in Ogbomosho.

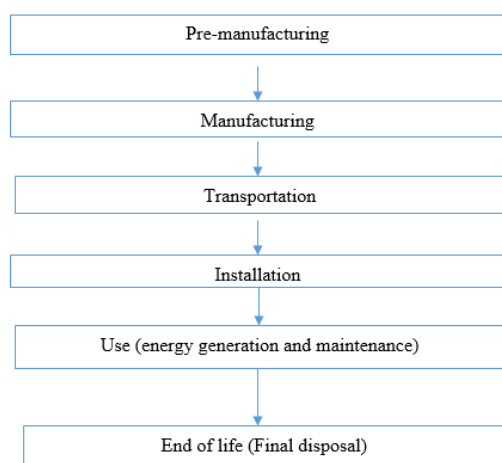


Figure 2: Life cycle stages of a solar PV module

2.3 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 Ogbomosho, 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 m² of the PV module was calculated as shown in equation (1)

$$\begin{aligned} \text{Area} &= \text{Power} \div (\text{Efficiency} \times \text{Irradiance}) \quad (1) \\ &= 12\text{W} \div (0.15 \times 1000\text{W/m}^2) = 0.08\text{m}^2 \end{aligned}$$

2.4 Environmental Indicators

The following indicators were chosen to investigate the environmental aspects of the PV module: cumulative energy demanded (CED), energy payback time (EPBT), CO₂ emission rate, CO₂ payback time (CO₂PBT), global warming potential (GWP), greenhouse gas (GHG) emission rate, and the module's impact on human health.

3.4.1 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)

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

E_i = Energy required for each life cycle stage according to OpenLCA.

2.4.2 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. Eqs. (2) and (3) determined the Energy payback time, and Net energy gain, respectively

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

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

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

2.4.3 Global warming potential (GWP)

Greenhouse gases (GHGs) such as CO₂, CH₄, N₂O, HFCs, and SF₆ 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 CO₂ equivalents for the global warming equivalent. GWP data were used as gCO₂ equivalent/functional unit to quantify the effects of GHGs on global warming, IPCC (1996)

2.4.4 Greenhouse Gas (GHG) emission rate

GHG emission rate is determined using equation (5)

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

$\text{LCCO}_{2\text{ equivalent}}$ is the total CO₂ 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)

2.4.5 CO₂ Payback Time (CO₂PBT)

The number of years needed for a system's CO₂ emissions to be offset by its CO₂ reductions is called CO₂PBT. For CO₂PBT, the system's CO₂ emissions have been estimated, and the polycrystalline silicon PV system's annual CO₂ reduction is calculated by multiplying its kWh output by the Nigerian grid mix's GWPs. This study calculated the net CO₂ reduction from a PV system using equation (6)

$$\text{CO}_2 \text{ payback time (CO}_2\text{PBT)} = \frac{\text{CO}_2 \text{ total emissions}}{\text{CO}_2 \text{ annual reduction}} \quad (6)$$

The module's CO₂ total emissions (gCO₂ equivalent) are the entire CO₂ emissions throughout its lifecycle, and the CO₂ annual reduction is the annual CO₂ reduction achieved through the implementation of the system (gCO₂ equiv./year).

2.5 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/m² 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/m², and 0.75, respectively.

2.6 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 1kWh of energy generated from the PV module (Alsema *et al.*, 2007). The 12W PV module established the reference flow, or PV module size needed to generate 1kWh. Table 1 depicts the 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

2.7 Life Cycle Inventory Analysis

2.7.1 Data Collection and Sources

A life cycle inventory (LCI) analysis quantified the inputs and outputs at each stage of the 12W photovoltaic module's life cycle. Data primarily derived from life cycle inventory databases, including the Ecoinvent database (Version 3.7) and the Swiss Centre for Life Cycle Inventories, supplemented by peer-reviewed studies, industry reports, the National Renewable Energy Laboratory (NREL), the International Energy Agency (IEA), and literature on life cycle assessment (LCA), were utilized to model the photovoltaic (PV) module.

2.7.2 Pre-manufacturing and manufacturing stages

An arc furnace will convert quartz sand silica to metallurgical-grade silicon (MG-Si) for the production of polycrystalline silicon (mc-Si) PV modules after the extraction of silica (Koroneos et al., 2006). Afterward, the Siemens technique will purify MG-Si to Poly-Si by utilizing hydrogen, hydrochloric acid, and a significant amount of energy (Koroneos et al., 2007). The melting and casting of Poly-Si into large masses will produce the mc-Si ingot, which does not necessitate the high, sustained temperatures necessary for the production of single-crystal silicon (sc-Si) (Tao, 2008). mc-Si ingots are cut into wafers with thicknesses that are determined by the size and capacity of the PV module. Cell production procedures would be implemented on these substrates. In order to optimize light absorption, these wafers will be incised and textured. Subsequently, the p-n junction required for electricity generation will be established by an emitter layer, and the conductivity will be enhanced by a rear surface through its contact. Tao (2008) recommended the application of an antireflective coating to enhance light absorption and decrease reflection. After preparation, the cells will be laminated with a rear foil, EVA, and glass. Heating the assembly to dissolve the EVA will encapsulate it, thereby ensuring its durability. After the addition of aluminum framing and cable

connections, the photovoltaic effect generated electricity from the PV module. A completely constructed polycrystalline photovoltaic module that utilizes solar energy was created from raw quartz sand..

2.7.3 Transportation stage

The module's transportation stage from the factory in China to Ogbomosho, 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 Ogbomosho, under G: 237.7 km (Google Maps)

2.7.4 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.

2.7.3 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 12W. Using the given solar irradiation of 4.846 kWh/m²/day, The daily energy output was calculated using equation (7)

$$\text{Daily energy output} = \text{Efficiency} \times \text{Average GHI} \times \text{Area} \quad (7)$$

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

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

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

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

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

$$E_{\text{total}} = 636.7644 \text{ kWh}$$

$$1 \text{ kWh} = 3.6 \text{ MJ}$$

$$636.7644 \text{ kWh} \times 3.6 \text{ MJ/kWh}$$

$$E_{\text{total}} = 2292.35184 \text{ MJ}$$

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.

2.7.4 End of life stage

The end-of-life phase of the photovoltaic module encompasses the actions related to its decommissioning and disposal, which primarily entail landfill procedures. The data needed at the end-of-life phase will include the energy input and the emissions (CO₂ and other pollutants) produced during the decommissioning and disposal of the photovoltaic module. The OpenLCA software computed the impact scores for the selected indicators throughout each life cycle stage utilizing various LCIA methodologies, including the CED method, the IPCC approach, the IMPACT 2002+ method, the ReCiPe method, and the CML method. This study aims to evaluate the life cycle carbon footprint and environmental product profile (EPP) of a 12W rooftop polycrystalline solar photovoltaic module.

3. Results and Discussions

This section presents and discusses the findings of the LCA effect evaluation for the 12W polycrystalline solar photovoltaic module.

3.1 Cumulative Energy Demand (CED)

The energy demand (MJ per module) is plotted against the life cycle stage in Figure 3. The 12W polycrystalline silicon photovoltaic module in this investigation was determined to have a Cumulative Energy Demand (CED) of 1232 MJ over its entire life cycle. Polysilicon processing (500 MJ), ingot, and wafer production (450 MJ total) were the most energy-intensive phases, accounting for 60.23% of the total energy requirement. These procedures involve energy-intensive activities, such as the production of metallurgical-grade silicon (MG-Si), purification through the Siemens process, and wafer dicing. These activities are documented as significant contributors to the energy consumption of photovoltaic modules. Because of the limited

module area (0.08 m²) and the substantial energy requirements for silicon purification and wafer manufacturing, the CED per unit area was determined to be 15,400 MJ/m². This is a significant increase. The energy profile of photovoltaic (PV) systems could potentially be reduced by localized production and enhanced recycling technologies, even though transportation (15 MJ, 1.22%) and end-of-life disposal (10 MJ, 0.81%) contributed marginally to the overall cumulative energy demand (CED). Advancements in wafer dicing, silicon recovery, and manufacturing efficiency have significantly reduced the CED of polycrystalline PV modules.

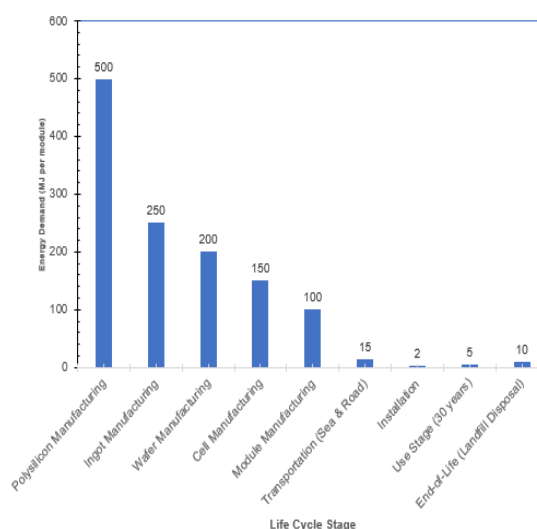


Figure 3 Plot of Energy Demand (MJ per module) against Life Cycle Stage

It has been demonstrated that integrating renewable energy into photovoltaic manufacturing plants can reduce cumulative energy demand by up to 30% (Kim et al., 2014). Additionally, improved recycling and localized production will reduce transportation-related energy consumption. According to this study, the most energy-intensive steps in the production of photovoltaics are silicon purification and wafer processing, which call for efficiency improvements. Localized manufacturing, recycling programs, and improved production techniques can all substantially reduce sustainability effects while lowering the total energy needs of polycrystalline solar modules.

3.2 The Energy Payback Period (EPBP)

The 12W polycrystalline PV module's net energy benefit and energy return time are illustrated in Figure 4. The Energy Payback Time (EPBT) for the 12W polycrystalline silicon solar module in this study is 16.12 years, which is the duration required to generate energy equivalent to its Cumulative Energy Demand (CED) of 1232 MJ. Throughout its 30-year lifecycle, the module generates a Net Energy Benefit (NEB) of 1060.35 MJ, which is equivalent to 1.86 times the initial energy investment, as it produces 76.4117 MJ of primary energy annually. The elevated EPBT is primarily due to energy-intensive production processes, particularly polysilicon purification and wafer fabrication, which necessitate substantial energy consumption. Despite the protracted energy payback period, the module maintains a net positive energy yield, which further solidifies its viability as a sustainable energy solution.

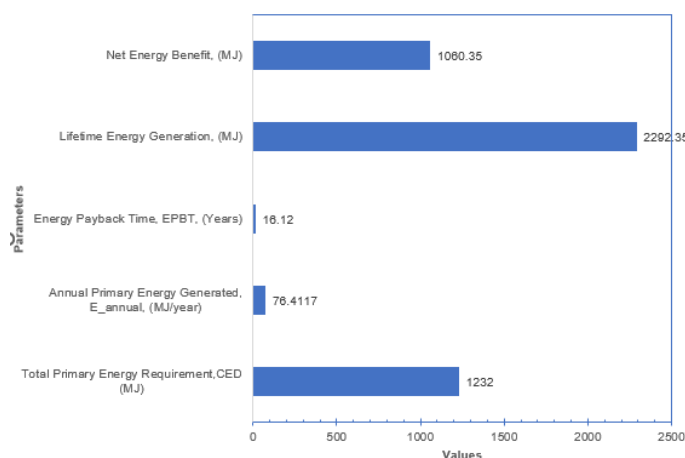


Figure 4 Energy Payback Time and Net Energy Benefit of the 12W Polycrystalline PV Module

The EPBT obtained was 16.12 years, which is substantially greater than the reported values for modern PV modules. High-efficiency monocrystalline and perovskite-based modules exhibit substantially reduced energy payback times (EPBT) of 0.5–2 years in additional studies on commercial photovoltaic systems (Fthenakis et al., 2011; Tao et al., 2022). The diminutive module size

(12W), moderate efficiency (15%), and substantial embodied energy during production are the primary factors contributing to the elevated EPBT in this study. In order to align with global trends in photovoltaic sustainability, the energy return must be enhanced through measures such as silicon recycling, streamlined production, and improved transport logistics, as well as increased efficiency (>18%).

3.3 Global Warming Potential (GWP)

The Global Warming Potential (GWP) of the 12W polycrystalline silicon photovoltaic (PV) module analyzed in this work is 136 kg CO₂-equivalent during its entire life cycle, as illustrated in Figure 5. Greenhouse gas emissions per functional unit (1 kWh of electricity generated) total 0.214 kg CO₂-equivalent per kWh, derived by dividing the total greenhouse gas emissions by the total energy output of 636.7644 kWh (Figure 5). The principal sources of these emissions are the production processes, encompassing polysilicon refining, wafer-cell fabrication, and module assembly, which together contribute significantly to overall emissions. Transportation, installation, and end-of-life disposal contribute relatively tiny yet important increments to the overall footprint. Despite these emissions, the module is a more eco-friendly source than energy produced from fossil fuels.

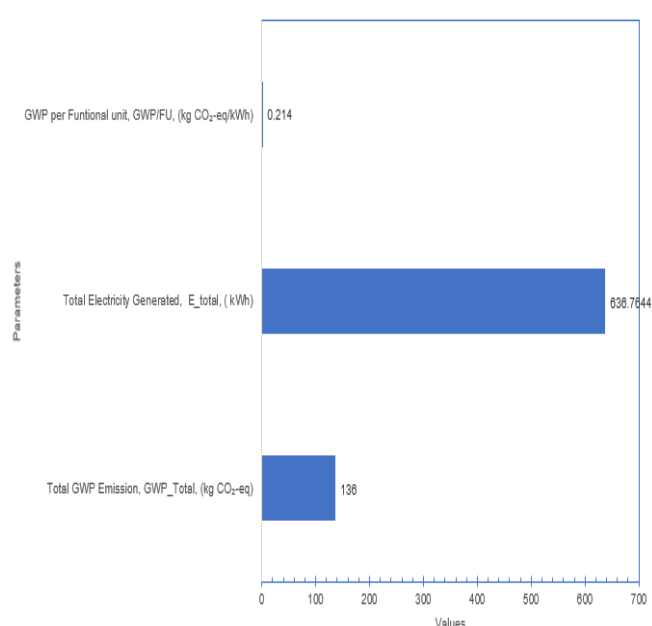


Figure 5: Global Warming Potential per Functional

Unit of the 12W Polycrystalline PV Module

The 0.214 kg CO₂ -eq/kWh emissions reported in this analysis surpass those of new photovoltaic systems in comparison to the literature (Fthenakis & Kim, 2006; NREL, 2020). Prior research has estimated the greenhouse gas emissions of commercial multi-crystalline silicon photovoltaic modules to be 0.02–0.1 kg CO₂ -equivalent per kilowatt-hour. However, high-efficiency monocrystalline and thin-film photovoltaic systems have significantly lower emissions, ranging from 0.01 to 0.06 kg CO₂ -equivalent per kilowatt-hour (Frischknecht et al., 2020). The energy-intensive production procedures, limited scale (12W), and low module efficiency (15%) are the sources of the increased emissions in this study. To reduce the greenhouse gas (GHG) footprint, it is necessary to implement measures that are consistent with global trends in PV technology, including augmenting recycling processes, employing renewable energy for manufacturing, optimizing logistics, and enhancing efficiency (>18%).

3.4 The Greenhouse Gas Payback Period (GHG PBP)

The 12W polycrystalline silicon photovoltaic module has a Greenhouse Gas Payback Time (GHG PBT) of 11.72 years, which means it will take nearly 12 years to counteract the 136 kg CO₂ -equivalent emissions generated over its lifetime. The estimate uses Nigeria's grid emission factor of 0.547 kg CO₂ /kWh to reflect the carbon intensity of grid power. The module's annual energy generation of 21.22548 kWh prevents 11.61 kg CO₂ -eq emissions from fossil fuel combustion, reducing reliance on fossil fuel-derived electricity. Despite its relatively high greenhouse gas production before tax, the module achieves net carbon emission reductions during its entire 30-year lifespan, qualifying as a renewable energy source. When compared to available literature, this GHG PBT of 11.72 years is significantly higher than the values stated for current PV systems. According Fthenakis & Kim, 2007; Frischknecht et al., 2020), the greenhouse gas payback time (GHG PBT) for

multicrystalline silicon modules ranges from 1.5 to 5 years, whereas thin-film photovoltaics have significantly lower payback lengths. The increased GHG PBT in this study is mostly due to low module efficiency (15%), small system size (12W), and energy-intensive manufacturing procedures. To improve GHG payback performance, it is important to deploy superior efficiency modules (>18%), enhanced recycling procedures, and manufacturing powered by renewable energy, while closely complying with global sustainability norms..

3.5 Greenhouse Gas (GHG) Emission Rate

The 12W polycrystalline silicon PV module has a lifetime energy output of 636.7644 kWh over 30 years and a total life cycle GHG emission of 136 kg CO₂ -eq, resulting in a GHG emission rate of 0.214 kg CO₂ -eq per kWh, as illustrated in Figure 6. The value emphasizes the module's carbon imprint, which is influenced by the average solar irradiation (4.846 kWh/m²/day), energy-intensive production processes (polysilicon purification and cell-wafer fabrication), and transit from China to Ogbomoso. The photovoltaic module is classified as a considerably lower-carbon energy source due to the 61% reduction in greenhouse gas emissions per unit of power produced compared to grid electricity.

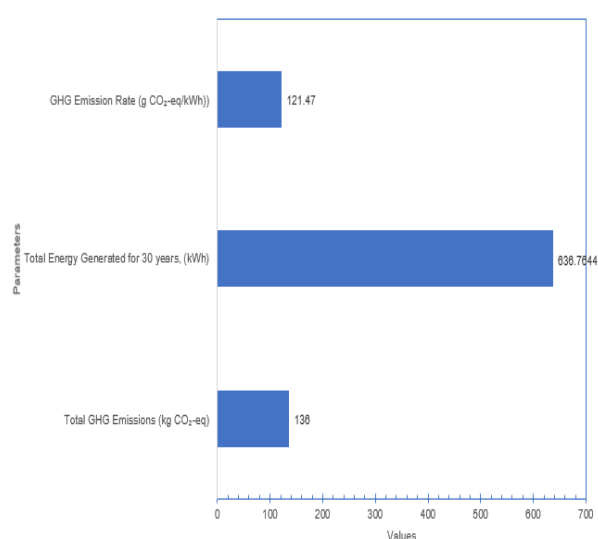


Figure 6: The GHG Emission Rate

The emission factor of 0.214 kg CO₂ -eq/kWh in

this study surpasses that of the majority of current polycrystalline silicon PV systems, which typically fall within the range of 0.02 to 0.12 kg CO₂ -eq/kWh (Fthenakis et al., 2008; Frischknecht et al., 2020). In high-irradiation regions, NREL (2015) identified a minimal emission of 0.04 kg CO₂ -equivalent per kilowatt-hour for large-scale systems, while Peng et al. (2013) reported that Chinese photovoltaic systems produce between 0.05 and 0.18 kg CO₂ -equivalent per kilowatt-hour. The minuscule 12W module size, comparatively low efficiency (15%), and production reliant on fossil fuels are the primary factors contributing to the elevated emissions. In order to reduce the carbon footprint of small-scale photovoltaic systems, it is imperative to implement high-efficiency modules (>18%), optimize energy sources in the manufacturing process (e.g., solar or hydroelectric), and promote material recycling..

4. Conclusions

The assessment of the energy repayment period (EPP) and life cycle carbon footprint of a 12W rooftop polycrystalline solar photovoltaic module offers critical insights into its environmental sustainability. The study underscored that solar photovoltaic (PV) systems mitigate greenhouse gas emissions during operation; however, their environmental impact is significantly impacted by the energy-intensive manufacturing processes, transportation, and disposal at the conclusion of their lifecycle. The balance-of-system (BOS) components, module manufacturing, and silicon purification are the primary sources of emissions, according to the life cycle carbon footprint analysis. The predicted EPP indicated that the module could recoup its embodied energy within a relatively brief timeframe, depending on the local solar irradiance levels. Polycrystalline photovoltaic (PV) technology provides a favorable energy return on investment and significantly reduces long-term carbon emissions in comparison to conventional fossil fuel-based energy sources.

It is imperative to prioritize the optimization of material recycling. To improve the sustainability of solar PV modules, the integration of healthier energy sources, the extension of module lifespan, and the improvement of energy efficiency in production are required. The carbon footprint and energy payback period may be further reduced and

the energy payback period may be improved by future advancements in photovoltaic technology and recycling strategies, rendering solar energy a more sustainable solution to the world's energy requirements.

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