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Geographic Influence on the Life Cycle Assessment of a 12W Polycrystalline Solar Photovoltaic Module in Southwest Nigeria

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***Abstract*: This study examined the geographic impact on the life cycle environmental performance of a 12W polycrystalline solar photovoltaic (PV) module installed in six designated locations throughout Southwest Nigeria: Ogbomosho (Oyo State), Ikeja (Lagos State), Abeokuta (Ogun State), Osogbo (Osun State), Akure (Ondo State), and Iworoko (Ekiti State). As the demand for renewable energy technologies escalates, comprehending the geographical influences on the sustainability of solar PV systems is essential for maximizing its implementation. Nevertheless, there is a paucity of localized data regarding the environmental performance of small-scale photovoltaic modules across Nigeria's varied climatic zones. This study filled the gap by assessing life cycle indicators including cumulative energy demand (CED), energy payback time (EPBT), global warming potential (GWP), greenhouse gas payback time (GHG-PBT), greenhouse gas emission rate (GHG-ER), CO_2 emission rate, and CO_2 payback time. The method considered a system boundary encompassing the pre-manufacturing and manufacture stages in China, transit logistics from China to Nigeria, as well as the installation, operation, and end-of-life phases at six locations in Nigeria. The data indicated that CED values are uniform across sites, varying from 1231.86 MJ in Ikeja to 1232.10 MJ in Iworoko, with manufacturing accounting for around 97% of overall energy demand. EPBT values exhibit considerable variation owing to disparities in solar irradiation, with Ikeja documenting the highest value at 17.62 years and Iworoko the lowest at 15.95 years. GWP values varied from 66.31 $kgCO_2eq$ in Akure and Osogbo to 136 $kgCO_2eq$ in Ogbomosho, mostly affected by transportation distances and factory emissions. Correspondingly, GHG-PBT fluctuated from 5.66 years in Iworoko to 11.72 years in Ogbomosho, whilst GHG-ER ranged from 0.1031 to 0.2137 $kgCO_2eq/kWh$. The results underscore the environmental benefits of installing solar modules in high-irradiance regions and stress the significance of sustainable manufacturing processes and localized photovoltaic production to mitigate carbon footprints.**

***Keywords*: Environment, Solar, Photovoltaic, LCA, Energy, Payback.**

1. Introduction

Solar photovoltaic (PV) technology has become increasingly popular as a sustainable and green alternative to fossil fuels as global efforts to combat climate change continue to escalate. Polycrystalline modules have grown in popularity among the various PV technologies as a result of their favorable efficiency-to-price ratio and relatively low cost However, the entire life cycle of PV modules—from raw material exploitation through manufacturing, transportation, use, and end-of-life disposal—has associated environmental impacts, even though solar energy is often considered environmentally benign (Anctil and Fthenakis 2012). The environmental footprint of PV technologies must be comprehensively assessed through a Life Cycle Assessment (LCA). Solar photovoltaic (PV) systems have the potential to significantly reduce greenhouse gas emissions and improve energy security in developing countries such as Nigeria, where fossil fuels dominate the energy matrix However, the environmental performance of solar modules can vary considerably based on their geographical location, as this is influenced by variations in solar irradiance, temperature, humidity, and atmospheric conditions. These factors directly affect the longevity of the system and the energy output. In this regard, a location-specific life cycle assessment (LCA) offers a more precise assessment of the sustainability of photovoltaic (PV) technology (Corominas *et al*. 2020).

A standardized methodology known as Life Cycle Assessment (LCA) is employed to assess the environmental implications of a product throughout its lifecycle, which encompasses the exploitation of raw materials, production, utilization, and disposal (ISO 140040, 2006). According to Kim and Fthenakis (2019), life cycle assessment (LCA) is essential for evaluating the sustainability of a variety of technologies and deployment strategies in the context of solar photovoltaic systems, as it provides a thorough comprehension of their environmental impact. Because of their moderate efficiency and pervasive adoption, polycrystalline silicon photovoltaic modules have been the focus of extensive research. The energy payback time (EPBT) and greenhouse gas (GHG) emission reductions of these systems are significantly influenced by their operational context and material composition (Drew *et al*. 2022).

Global environmental challenges are anticipated to escalate unless definitive measures are implemented. Consequently, it is

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imperative to tackle the issues posed by contemporary civilization and increasing industrial activity while minimizing costs, maximizing production efficiency, and mitigating environmental impact (Garba *et al*. 2020). A commonly employed standardized tool for evaluating the environmental effects of human activities is life cycle assessment (LCA). LCA assesses the environmental effects of products and services across their whole life cycle, referred to as "cradle-to-grave analysis" (International Organization for Standardization, 2006a). This analysis evaluates energy and material inputs and outputs across the life cycle, quantifying impacts such as ozone depletion, global warming, and particulate matter at the midpoint level, as well as human health, ecosystem quality, and resource depletion at the endpoint level (Udo de Haes and Heijungs 2007; Finnveden et al. 2009). LCA serves as an essential instrument for decision-makers in the planning, strategizing, and redesigning of products and processes. A primary benefit of LCA is its ability to extend the system boundary to encompass all environmental consequences, hence mitigating "burden shifting" (Guinée *et al*. 2002; Zang *et al*. 2015).

LCA is utilized in sectors such as agriculture and food production (Brentrup *et al.* 2001; Henriksson *et al*. 2012), wastewater treatment facilities (Gallego-Schmid and Tarpani 2019;), pharmaceuticals (Emara et al. 2018), mining (Awuah-Offei and Adekpedjou 2011; Farjana *et al*. 2021), healthcare (Drew et al. 2022), oil and gas, medicine, information and communication technology (ICT), and the Internet of Things (IoT) (Chen *et al*. 2014). The increasing body of research underscores the significance of Life Cycle Assessment (LCA), the progression of impact assessment methodologies from regional to global levels, and the establishment of standardized protocols (ISO 14040 and 14,044) to direct LCA investigations. As the world transitions to carbon-neutral societies, circular economies, and the Fourth Industrial Revolution (4IR), Life Cycle Assessment (LCA) will remain essential in assessing the environmental sustainability of these paradigm shifts, technologies, and processes, while addressing trade-offs among various environmental issues (Corominas *et al.* 2020). In developing nations, there is an increasing interest in life cycle assessment (LCA) research and development, due to the recognition that an environmentally detrimental industrial system might generate more suffering than benefit for society (Arena 2000). Nonetheless, other concerns persist, including data quality, methodological selections, and the absence of effect categories that accurately reflect local circumstances.

Güereca *et al.* (2015) emphasized the persistent increase in the utilization and application of LCA in Mexico by both governmental and academic entities, whereas Shaukat (2023) encapsulated LCA research across multiple sectors of the Saudi Arabian economy. The research indicated a markedly restricted utilization of LCA in Saudi Arabia. Buckley et al. (2011) examined the abstraction and utilization of energy for wastewater treatment and pumping, identifying it as the most significant environmental burden in South Africa's water sector. Yacout (2019) examined the application of the LCA technique in Egypt and identified the primary problems associated with utilizing the instrument. Harding *et al*. (2015) emphasized the utilization of European-based technologies, including SimaPro, GaBi, and Ecoinvent, by South African LCA practitioners.

Nigeria is a prominent gas producer and exporter, as well as one of the rapidly advancing emerging economies worldwide, exhibiting an annual average gross domestic product (GDP) increase of 3% from 2021 to 2023 (PwC 2024). Nonetheless, it confronts burgeoning environmental concerns amid escalating demand for natural gas and essential minerals (such as lithium), swift industrialization, a swelling population, and an expanding middle class with improved living standards. Natural gas and critical minerals are essential for the clean energy transition, serving as a supplementary energy source for intermittent wind and solar power. Additionally, industrialization generates employment opportunities. However, the proliferation of gas flaring, oil spills, air, and water pollution, land use alterations, and waste management challenges linked to oil and gas extraction, mining, agriculture, and manufacturing have emerged as significant issues in Nigeria (Isah *et al*. 2024). Nonetheless, evaluating environmental consequences and the efficacy of mitigation solutions in Nigeria is problematic due to insufficient data and the nascent development of life cycle assessment studies and other sustainability evaluation tools. 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 30ºC, the output voltage falls. The photovoltaic modules have an exergy efficiency of 49.30%, but electrical efficiency reduces as solar radiation and temperature increase.

Moreover, disparities in economic priorities, environmental policies, and technological progress generate unique drivers, requirements, and constraints for Life Cycle Assessment (LCA) across industrialized, emerging, and developing nations. The disparities and commonalities among areas, income levels, and developmental phases result in differing environmental impacts and mitigation strategies. Consequently, in light of the anticipated rapid socioeconomic and technological advancements in Nigeria and their corresponding environmental repercussions, it is imperative to focus on the enhancement of the LCA tool to facilitate corporate decision-making and assist governmental policy development. A thorough and critical assessment of LCA studies in Nigeria is urgently required. As of now, there is no comprehensive evaluation that expressly addresses methodological choices in Nigerian LCA research. The majority of LCA research in Nigeria and Sub-Saharan Africa has been on large-scale grid-connected systems or generic models that fail to integrate local environmental variables. Nwokocha *et al.* (2018) assessed the environmental impacts of photovoltaic modules in Nigeria, although they overlooked spatial variance. Akinyele et al (2026) evaluated the life cycle energy and emissions of PV systems; however, they utilized global average information that may not accurately represent localized performance. This generated a knowledge deficit about the impact of region-specific variables on the life cycle performance of photovoltaic systems, particularly small-scale modules like the 12W polycrystalline panels commonly utilized in rural and off-grid contexts.

Lunardi *et al*. (2018) conducted a comparison of standalone silicon modules and chalcogenide/si tandem solar modules, which demonstrated enhanced efficiency and reduced environmental impacts, particularly in the areas of energy return time and greenhouse gas emissions. The environmental trade-offs associated with the production of tandem modules at scale or the recycling potential of chalcogenide materials were not examined in the study. In comparison to conventional energy sources, Rajput *et al*. (2018) demonstrated that the 3.2 kW CDTE's photovoltaic system in India's composite climate provides substantial environmental benefits, particularly in terms of reduced greenhouse gas emissions and energy recovery time. The manufacturing stage is the primary location of the system's environmental impacts. The study did not offer any insights into the end-of-life phase of the CTDE's system, which includes material recovery and recycling potential. The environmental impact of organic photovoltaics (OPVs) during the manufacturing process is lower than that of traditional PV technologies, as they employ less energy-intensive materials and processes. Parisi *et al*. (2013) evaluated dye-sensitized solar cells (DSSCS) from a life cycle perspective, highlighting their potential as a renewable energy technology with reduced environmental impacts in comparison to conventional photovoltaics. The analysis emphasized the importance of material selection and process optimization in reducing the energy and environmental costs associated with DSSCS. The evaluation did not examine the recycling potential of DSSC materials or offer strategies for end-of-life (EoL) remediation.

The substantial opportunity to mitigate environmental impacts is presented by organic photovoltaic (OPV) panels, which have lower material and energy requirements than conventional PV technologies, as emphasized by Tsang *et al*. (2018). The cradle-to-grave assessment underscores the benefits of OPV in terms of reduced greenhouse gas emissions and energy utilization during production. The end-of-life (EoL) management and recycling processes for OPV panels were not comprehensively examined in the analysis. The impacts of these structures were accounted for by electricity use, up to 90%. Htl-free PSC devices exhibited diminished environmental impacts when contrasted with other perovskite methods. The absence of comprehensive data on large-scale production processes for perovskite solar cells in the study limited the accuracy of environmental impact estimates. Furthermore, the potential end-of-life (EoL) scenarios and recycling strategies for PSC structures were not investigated. Zhang *et al.* (2017) conducted a comparative analysis of a variety of perovskite solar cell systems and discovered that the environmental impacts were substantially influenced by the design of the system and the material choices made. Devices with reduced lead content and enhanced energy efficiency demonstrated smaller environmental imprints. No evaluation of end-of-life management and recyclability was conducted in the study.

Although international research has progressively shifted towards regionally tailored LCA models, such initiatives are nonetheless constrained within the Nigerian setting. The lack of region-specific LCA data hinders decision-makers from accurately assessing the sustainability of solar PV systems in particular areas of Nigeria. A regionally informed Life Cycle Assessment can ascertain the environmental viability of implementing small-scale photovoltaic modules in Southwest Nigeria, particularly for rural electrification initiatives. Rectifying this deficiency is crucial for formulating environmentally sustainable energy solutions according to the region's distinct geographic and climatic characteristics. This study examined the impact of geography on the life cycle assessment of a 12W polycrystalline solar PV module and the study is aimed at evaluating the life cycle assessment of a 12W rooftop polycrystalline solar photovoltaic module across six distinct locations. The results are delineated in section 3.0 for each chosen location, including Ogbomosho (Oyo State), Ikeja (Lagos State), Abeokuta (Ogun State), Osogbo (Osun State), Akure (Ondo State), and Iworoko (Ekiti State).

2. Methodology

This methodology section described the environmental impact assessment procedure for the 12W solar PV module across six different geographic areas which comprise Ogbomosho (Oyo State), Ikeja (Lagos State), Abeokuta (Ogun State), Osogbo (Osun State), Akure (Ondo State), and Iworoko (Ekiti State).

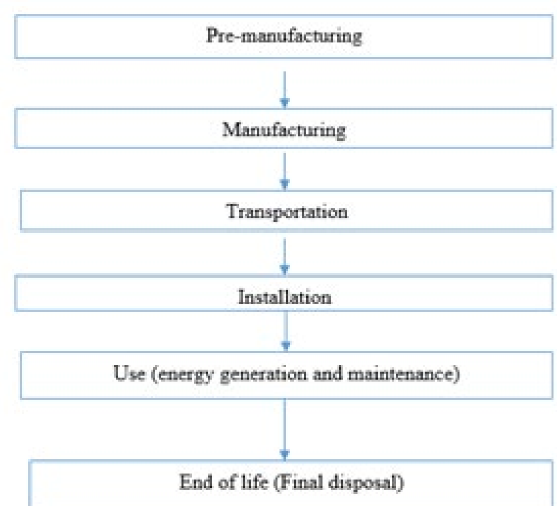

Fig. 1. Life cycle stages of a solar PV module

A. *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.

B. System Boundary

The PV module system boundaries include pre-manufacturing, production, transportation, installation, usage, and disposal as presented in Fig. 1. 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.

C. 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 barrels jack ports and 2 USB ports.

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

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

D. 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.

1) Cumulative Energy Demanded (CED)

CED is the major energy used in a product's life cycle, from premanufacturing 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).

$$CED = \sum E_i \quad (2)$$

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

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 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

Energy payback time

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

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

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

3) 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, IPCC (1996)

4) Greenhouse Gas (GHG) Emission Rate

GHG emission rate is determined using equation (5)

GHG emission rate

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

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

5) 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 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).

E. 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.

F. 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 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

G. Life Cycle Inventory Analysis

1) 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.

2) 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 (Koroneos *et al.,* 2007). 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.

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) and other locations are presented in Table 2.

4) Installation

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

5) 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 12W 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)

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

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

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

$$= 0.058152 \times 365 = 21.22548\ kWh/year$$

Actual total energy output for 30 years = Annual energy Output ×30 years

$= 21.22548$ kWh/year × 30 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 the solar radiation properly.

6) 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 region of Southwest Nigeria is a prospective location for the deployment of solar PV, as it is characterized by moderate to high solar radiation and relatively stable climatic conditions. It is imperative to evaluate their complete life cycle performance under local environmental conditions, to guarantee the long-term sustainability and environmental viability of these technologies in the region. In specified locations within Southwest Nigeria,

3. Result and Discussions

The findings of the LCA effect assessment for the 12W polycrystalline solar photovoltaic module are presented and discussed in this section. Table 2 delineates the distance (km), and GHI (kWh/m^2/day) for each selected location such as Ogbomosho (Oyo State), Ikeja (Lagos State), Abeokuta (Ogun State), Osogbo (Osun State), Akure (Ondo State), and Iworoko (Ekiti State). The Cumulative Energy Demand (CED) across various locations is depicted in Figure 1. The Cumulative Energy Demand (CED) is the total primary energy required throughout the life cycle of the 12W polycrystalline silicon PV module at various locations.

The total CED exhibits a minor fluctuation in response to changes in transport distances. The CED of Iworoko, Ekiti State (1232.10 MJ) was the highest due to its additional road transportation distance, while Ikeja, Lagos State (1231.86 MJ) had the lowest CED due to its proximity to the seaport. The pre-manufacturing and manufacturing stages are the significant energy consumers, contributing 1200 MJ of the overall values, which is why the CED values in all the areas are relatively uniform. The transport phase was responsible for only minor variations in the aggregate CED, which ranged from 1231.86 MJ to 1232.10 MJ, as illustrated in Figure 1. The findings are consistent with previous Life Cycle Assessment (LCA) studies on PV modules, which have identified the majority of the energy required in polysilicon manufacturing and module assembly (Frischknecht *et al*., 2020; International Energy Agency [IEA], 2019).

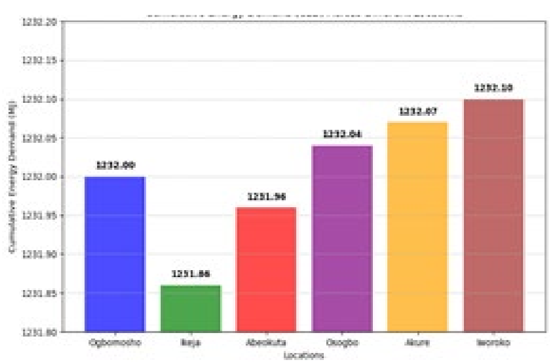

Fig. 2. Plot of the CED across different locations

The Energy Payback Time (EPBT) and The Net Energy Benefit (NEB) are illustrated in Figure 2. The Energy Payback Time (EPBT) of the areas under investigation varies from 15.95 years for Iworoko in Ekiti State to 17.62 years for Ikeja in Lagos State. The variation is regulated by the disparity in the level of solar irradiation (Global Horizontal Irradiance, GHI) between locations that have a significant impact on the total amount of electricity generated. The minimum EPBT of 15.95 years in Iworoko is a result of a maximum of 4.897 kWh/m^2/day in GHI, which may be higher in the case of yearly energy. Alternatively, Ikeja has the highest EPBT of 17.62 years as a result of its lower GHI of 4.435 kWh/m^2/day and subsequently lower energy yield in subsequent years. The Net Energy Benefit (NEB), which is the cumulative amount of net energy harvested throughout the PV module's lifecycle, exhibits a similar pattern. Iworoko has the highest NEB at 1083.20 MJ, while Ikeja has the lowest at 856.14 MJ. This confirms that PV systems in locations with a higher GHI generate a greater long-term energy payback. Figure 2 illustrates the graphical representation of EPBT and NEB. The EPBT values are slightly higher than the 2–5 years defined for large-scale crystalline silicon PV modules under optimal solar conditions, as compared to existing studies (IEA, 2019). In other analogous studies of PV modules in Sub-Saharan Africa, EPBT ranged from 12 to 18 years, with variations based on module efficiency and solar radiation (Akinyele *et al.,* 2017).

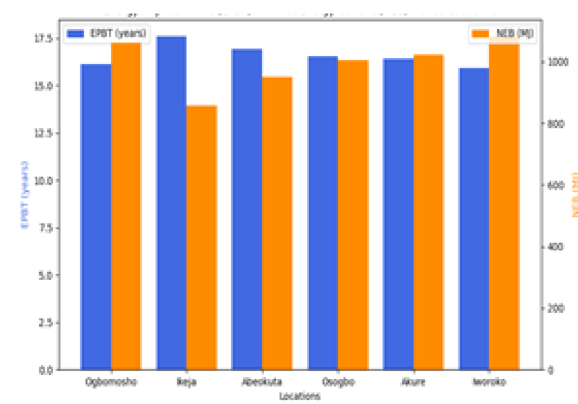

Fig. 3. Energy payback time and net energy benefit of the 12w polycrystalline PV module

The plot of the global warming potential (GWP) against locations is depicted in Figure 3. The entire greenhouse gas (GHG) emission (kg CO_2-equivalent) of the 12W polycrystalline PV module life cycle by location is denoted by the Global Warming Potential (GWP). The GWP is highest in Ogbomoso, Oyo State, at 136 kg CO_2-eq, and lowest in Osogbo (Osun state) and Akure (Ondo state) at 66.31 kg CO_2-eq, as illustrated in Figure 3. Pre-manufacturing and manufacturing are the most emission-intensive phases, with these variations primarily resulting from the transportation distances within Nigeria. The findings underscore that manufacturing generates the highest proportion of emissions, while transport has a

Table 2
Distance (km), and GHI (kWh/m^2/day) for each location

Locations	Distance from China to location (km)	GHI (kWh/m^2/day)
Ogbomosho (Oyo state)	20562.7	4.846
Ikeja (Lagos state)	20353.1	4.435
Abeokuta (Ogun state)	20446	4.613
Osogbo (Osun state)	20570	4.730
Akure (Ondo state)	20637	4.762
Iworoko (Ekiti state)	20673	4.897

negligible effect. These findings are consistent with previous research on PV life cycle analysis, which suggests that silicon PV module production is responsible for the greatest proportion of emissions (Frischknecht *et al*., 2020). These findings are consistent with previous research on PV life cycle analysis, which has identified the manufacturing of silicon PV modules as the primary source of emissions (Frischknecht *et al.,* 2007).

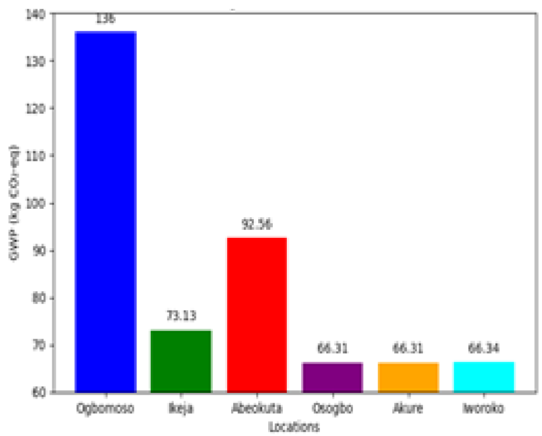

Fig. 4. Global warming potential (GWP) across locations

The chart of Greenhouse gas repayment time (GHGPBT) against locations is depicted in Figure 4. The Greenhouse Gas Payback Time (GHG PBT) indicator indicates the duration of time required for the electricity generated from a PV module to reimburse the total GHG emissions released during its life cycle. The GHG PBT in this study varies from 11.72 years in Ogbomosho, Oyo State, to 5.66 years in Iworoko, Ekiti State. The solar irradiation and transport distance are both influenced by these variations, as regions with higher solar irradiance and shorter road distances have lower overall emissions and higher yearly energy production, thereby reducing GHG PBT. Iworoko has a slightly higher GHI of 4.897 kWh/m²/day, which results in a faster offset of lifecycle emissions. Conversely, Ogbomosho has a higher GHG PBT due to its lengthier road distance and limited solar resources. Figure 5 illustrates the outcomes. The results are indicative of moderate to high GHG PBT levels in comparison to regions with more favorable solar conditions or local production, as evidenced by related work. Frischknecht *et al*. (2020) reported GHG PBT values that range from 2 to 8 years for specific regions in Europe and North America. These regions are characterized by moderate solar irradiation and high manufacturing efficiency.

The plot of Greenhouse gas emission rate (GHG ER) versus locations is depicted in Figure 5. The GHG Emission Rate is the amount of greenhouse gas emissions produced per unit of electricity generated by the 12W polycrystalline silicon PV module at various locations. The findings indicate that Ogbomoso, Oyo State, has the maximum emission rate (0.2137 $kgCO_2$-eq/kWh), while Iworoko, Ekiti State, has the lowest (0.1031 $kgCO_2$-eq/kWh). Figure 5 illustrates that region with higher solar irradiation levels (e.g., Ekiti and Ondo States) would experience reduced emission rates as a result of the increased electricity generation, which would reduce the per-kWh carbon footprint. The primary cause of minor discrepancies in GHG ER among locations is the variation in cumulative electricity generation, rather than transportation emissions, which only contribute insignificantly to life cycle emissions. The results are consistent with the Anctil and Fthenakis (2012) reported that the potential for polycrystalline PV modules to generate GHG emission rates as low as 0.05 $kgCO_2$-eq/kWh by deploying them in high-irradiance sites is a result of their higher energy yields. All of these comparisons underscore the fact that PV technology continues to be a viable low-carbon alternative to fossil fuels, despite the potential for further environmental benefits to be achieved through domestic production and efficiency improvements.

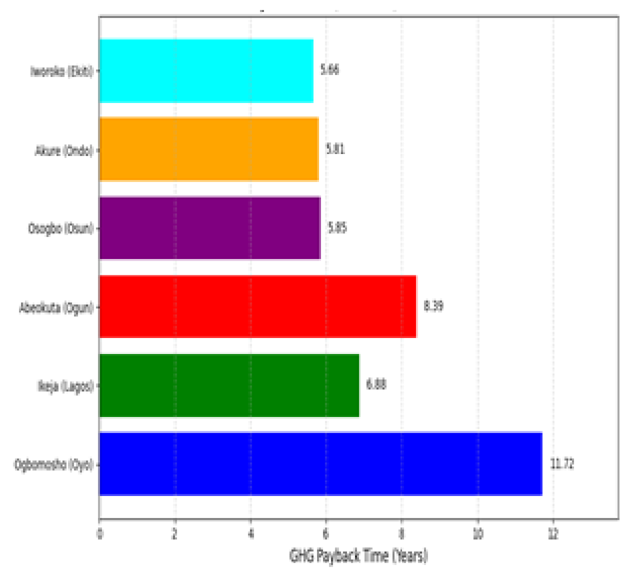

Fig. 5. Greenhouse gas payback time (GHGPBT) across locations

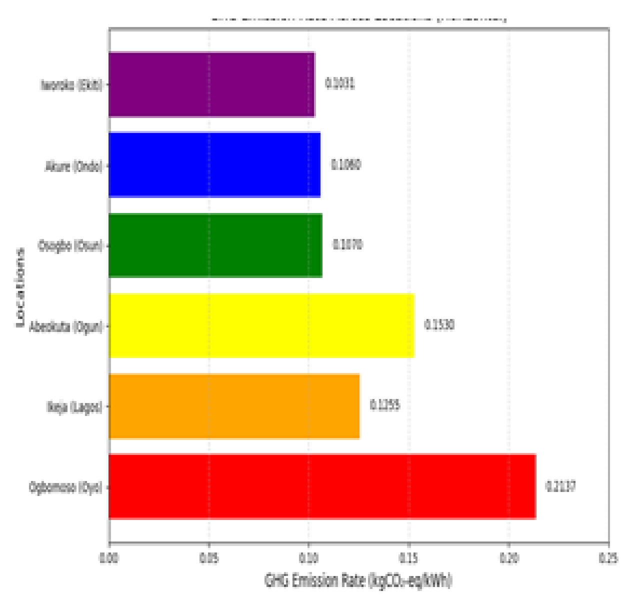

Fig. 6. Greenhouse gas emission rate (GHG ER) across locations

4. Conclusions

The results of this investigation lead to the following conclusions.

The cumulative energy demand (CED) was similar across all sites, ranging from 1231.86 MJ in Ikeja, Lagos State, to 1232.10 MJ in Iworoko, Ekiti State. Manufacturing consumed nearly 97% of total energy, with transportation accounting for only a small portion, underlining the importance of local PV production in energy conservation.

The EPBT varied by location, with Ikeja, Lagos State having the highest (17.62 years) and Iworoko, Ekiti State having the lowest (15.95 years). Higher sun irradiance leads to faster energy recovery, reinforcing the efficiency benefit of locating PV systems near higher solar resource concentrations.

The Global Warming Potential (GWP) ranged from 66.31 $kgCO_2eq$ in Akure and Osogbo to 136 $kgCO_2eq$ in Ogbomoso, highlighting the impact of transportation distance and energy use. The statistics suggest that manufacturing emits the most, highlighting the need for cleaner production techniques to minimize carbon emissions from PV modules.

Greenhouse Gas Payback Time (GHG PBT) varies by location, ranging from 5.66 years in Iworoko, Ekiti State, to 11.72 years in Ogbomoso, Oyo State. The fluctuations are primarily due to changes in solar irradiation, which affects overall electricity generation. The lower GHG PBT in high-irradiance locations demonstrates the advantage of deploying PV systems in solar-rich areas for earlier emission offset.

The Greenhouse Gas Emission Rate (GHG ER) ranged from 0.1031 $kgCO_2eq/kWh$ in Iworoko, Ekiti State, to 0.2137 in Ogbomoso, Oyo State. Sites with higher sun irradiation produce more electricity and emit less per kWh. These studies demonstrated that installing PV modules in higher solar potential areas reduces lifecycle emissions.

Additional research effort requires the following recommendations,

i. More research is needed to evaluate how using renewable energy sources in PV manufacturing affects overall emissions.
ii. High-efficiency solar cell technologies could minimize EPBT and GHG PBT in small-scale PV systems.
iii. To compare the benefits of domestic and imported PV modules, a life cycle assessment should be performed.

To boost sustainability, look into end-of-life management options like as PV module recycling and reuse.

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