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TECHNO ECONOMIC COMPARATIVE ANALYSIS OF PV MODULE INSTALLATION TECHNIQUES

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Abstract

Nigeria faces rising electricity costs and diesel power dependence which creates a need to find affordable and effective renewable energy alternatives. The study conducts a techno-economic comparison of three photovoltaic (PV) systems which include rooftop, ground-mounted, and floating PV systems at a Nigerian site that represents Lagos weather conditions. The researchers used PVsyst software to simulate system performance while they performed economic assessment through HOMER Pro software. The results demonstrate that floating PV systems produced their maximum annual energy yield of 334 MWh and achieved 86 % performance ratio, because their advanced module cooling system prevented thermal losses through lower operating temperatures. The ground-mounted system reached 321 MWh of energy production and had an 82% performance ratio, while the rooftop system produced the least energy, which amounted to 294 MWh due to shading and increased thermal losses. Economic analysis revealed that floating PV had the lowest levelized cost of energy (₦147.41/kWh) and shortest payback period (1.99 years), which was closely followed by the ground-mounted system. The research results indicate that floating PV provides the optimal solution for organizations that seek to enhance their energy production and financial benefits in comparable settings.

Keywords
Photovoltaic (PV) systems, floating solar, ground-mounted PV, rooftop solar, techno-economic analysis, PVsyst, levelized cost of energy (LCOE), renewable energy systems

1. INTRODUCTION

The worldwide shift toward clean energy systems which produce low carbon emissions has led to increased use of solar photovoltaic technology because it effectively meets growing electricity needs and addresses climate change issues. The global PV systems market has become one of the fastest expanding renewable energy sectors because it achieved installed capacity of more than 1 terawatt (TW) in 2023 and reached about 1.6 TW which exceeded previous International Energy Agency (IEA) [1, 2] capacity forecasts. The market experiences rapid expansion because of three factors which include decreasing PV module prices and better efficiency rates and governmental support through feed-in tariffs and renewable portfolio standards and tax breaks. The growth of large-scale ground-mounted PV systems has contributed to this industry expansion which includes major projects like Solar Park Bhadla in India and Tengger Desert Solar Park in China which showcase solar power energy systems ability to deliver efficient and affordable solutions [1, 3].

In addition to utility-scale deployment, rooftop PV systems have gained widespread adoption in urban areas, contributing significantly to distributed generation and energy self-sufficiency. For instance, in Australia, rooftop PV systems account for over 20% of total household electricity consumption and more than 60% of national solar capacity [4]. These systems offer advantages such as reduced transmission losses and efficient use of existing infrastructure, although their performance can be constrained by roof orientation, structural limitations, and shading effects [5]. More recently, floating photovoltaic (FPV) systems have emerged as an innovative solution, growing from less than 100 MW in 2015 to over 3,000 MW in 2023. Notable installations include the 45 MW Sirindhorn Dam project in Thailand and the 41 MW Hapcheon Dam project in South Korea [6]. FPV systems benefit from enhanced cooling due to proximity to water bodies, resulting in improved module efficiency and reduced thermal losses, as well as lower dust accumulation, which can increase energy yield by approximately 5– 10%. However, higher installation costs, anchoring requirements, and site-specific constraints remain key challenges [7].

Sub-Saharan Africa shows PV deployment progress compared to worldwide advancements since the region only holds less than 2% of total global solar power capacity despite its ability to produce solar energy between 4.5 and 6.5 kWh/m²/day [6], [8]. The major barriers for large-scale implementation arise from three primary factors which include restricted financial resources and insufficient electricity network systems and unpredictable government regulations. The Malindi Solar Park project in Kenya which has a 50 MW capacity and the Jasper Solar Plant project in South Africa which has a 100 MW capacity both indicate that the region experiences higher investment interest and solar power adoption. Nigeria stands out as a country with excellent solar energy potential because it receives about 5.5 kWh/m²/day of solar radiation making it an ideal location for PV system installation [9]. The Rural Electrification Agency (REA) and the Energizing Education Programme (EEP) government programs have supported public institutions and communities to establish both ground-mounted and rooftop PV systems [10]. Urban areas have expanded their use of rooftop PV systems because these systems help solve problems caused by unstable grid electricity while floating PV systems at existing hydropower reservoirs like Kainji Jebba and Shiroro dams offer substantial untapped potential for development [11].

Multiple studies have examined how various PV installation techniques perform against each other. Floating PV systems generate 5 to 10 percent more energy than ground-mounted systems because their modules stay cooler according to research in [7] and tropical regions experience similar advantages from decreased thermal and soiling losses according to research in [12]. The rooftop systems enable distributed generation benefits yet their energy production decreases because of inadequate tilt angles and shading problems according to research in [13]. Ground-mounted systems reach their best performance through design and orientation flexibility yet their need for extensive land space creates potential environmental and social issues according to research in [3]. Economic analyses typically indicate that ground-mounted systems achieve the lowest levelized cost of energy (LCOE) for large-scale projects whereas rooftop systems enable cost reductions through decreased reliance on the grid According to research in [5]. Existing studies assess these configurations across different environmental and economic scenarios which makes comparability between studies impossible. Researchers have developed limited studies that combine technical simulation tools with economic modelling platforms to assess PV system performance and financial viability in Africa which has different resource and economic conditions than developed countries according to research in [8].

In view of these gaps, this study conducts a comprehensive techno-economic comparison of rooftop, ground-mounted, and floating PV systems under identical design, environmental, and economic conditions using a representative site in Lagos, Nigeria. Unlike previous studies, this work integrates detailed performance simulation using PVsyst with economic and lifecycle analysis using HOMER Pro to provide a holistic evaluation of system performance. The study aims to assess key technical indicators such as annual energy yield, performance ratio, and system efficiency, alongside economic metrics including capital expenditure (CAPEX), operational expenditure (OPEX), levelized cost of energy (LCOE), and payback period. The findings are intended to provide practical guidance for selecting optimal PV deployment strategies in regions with similar climatic and economic conditions.

2. MATERIALS AND METHOD

2.1 Site Selection and Meteorological Data Collection

The research is within the Third Mainland Bridge corridor, Lagos, Nigeria (latitude 6.53°N, longitude 3.40°E) with its big solar irradiation, stable climate, and near significant load centers as reasons for the selection. PVGIS provided the meteorological data and it was coupled with PVsyst 7.4.7. The dataset gave an hourly resolution of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), ambient temperature, wind speed, and relative humidity.

The annual average GHI obtained from PVsyst was 5.2 kWh/m²/day based the on the PVGIS meteorological data inputted with the ambient temperatures of the data fluctuating between 26°C and 30°C (mean 27.24°C). A floating PV system was considered, and a reduction of 5°C in module operating temperature was factored in to allow for the convective cooling effects of water bodies. Table 1 shows the average monthly meteorological dataset for the year 2020 gotten from PVGIS.

2.2 Load Profile Definition

The electricity demand of a medium-sized commercial building in Lagos Nigeria was modeled through the development of a representative load profile. The team created a synthetic load profile because they could not access actual real-time data, using existing literature and standard energy consumption patterns of commercial buildings to build the profile.

The building operates on a 24-hour cycle, with a continuous base load maintained throughout the day to support essential services such as security systems and standby equipment. Electricity usage reaches its highest point between 08:00 and 18:00 because offices use their equipment and lights and heating ventilation and air conditioning systems. The average daily energy consumption was estimated at approximately 2,620 kWh, corresponding to an annual demand of about 956 MWh.

The hourly load distribution used in the simulation is presented in Table 1. This profile was converted into a CSV format and imported into PVsyst as a user-defined load to ensure consistency across all simulated PV system configurations.

Table 1: Average Monthly Meteorological Dataset for the Year 2020 From PVGIS.

	Average Monthly GlobHor(Wh/m^2)	Average Monthly DiffHor(Wh/m^2)	T_Amb (^{0}C)
January	461.11	282.35	27.32
February	486.29	323.66	27.31
March	445.11	261.52	27.22
April	425.5	225.41	27.03
May	494.92	279.9	27.26
June	444.66	251.02	27.36
July	460.75	246.33	27.25
August	490.55	268.7	27.42
September	449.29	237.13	27.31
October	441.34	231.16	27.27
November	455.53	221.1	27.38
December	467.22	261.89	27.30

Table 2: Typical Daily Load Profile for the Modeled System

Hourly Load	0h	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	
	30.0	30.0	30.0	30.0	30.0	30.0	30.0	100.0	200.0	200.0	200.0	200.0	kW
	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	
	200.0	200.0	200.0	200.0	200.0	160.0	130.0	100.0	30.0	30.0	30.0	30.0	kW

2.3 PV System Design Parameters

Three photovoltaic (PV) system configurations—rooftop, ground-mounted, and floating PV—were modelled under identical conditions to enable a fair comparison. Each system was designed with a DC capacity of 207 kWp and an AC capacity of 220 kW. The key system components common to all configurations are as follows:

i. PV Modules: Jinko Solar JKM-615N-66HL4M-BDV, monocrystalline, 615 Wp, 21.3% efficiency.
ii. Number of Modules: 336 units.
iii. Inverters: Two Huawei SUN2000-110KTL-M0 units, each rated at 110 kW.
iv. Mounting: Fixed tilt, with tilt angles adjusted per configuration (rooftop 10°, ground-mounted 15– 20°, floating 10°).
v. System Lifetime: 25 years for all systems.

The system design was further adapted to reflect the thermal and structural characteristics of each configuration. Rooftop arrays operated at higher temperatures because of their limited airflow while ground-mounted systems achieved optimal performance through their designed inter-row spacing which reduced shading losses and floating PV systems used water for cooling while their water surface albedo was estimated to be 6%. The performance parameters presented in Table 3 were obtained from PVsyst simulation outputs using meteorological data for Lagos, Nigeria. PVsyst computes system performance based on solar irradiance, module temperature, and system losses. The PV array electrical output depends on the following factors:

$$P = G \times A \times \eta \qquad (1)$$

where (P) is the output power (W), (G) is the incident solar irradiance (W/m²), (A) is the effective module area (m²), and η is the module efficiency. The array voltage and current are derived from the electrical characteristics of the PV modules and inverter configuration, while temperature effects are incorporated through PVsyst's thermal model, which adjusts module performance based on ambient temperature and mounting conditions. The simulation results for the year 2020 provided monthly average data which included irradiance, power output, array voltage, and array current.

2.4 Simulation Setup in PVsyst 7.4.7

The complete testing process used PVsyst version 7.4.7 to conduct Detailed Design simulations which covered all 8760 hours of the year. The site location was defined using the geographical coordinates of Lagos, Nigeria, allowing PVsyst to automatically generate solar geometry and irradiation data. The project team established system capacity through string configuration and inverter loading ratio setup while keeping the DC/AC ratio between 0.89 and 0.95 to decrease inverter clipping losses.

The actual installation conditions were used for each configuration through different array layout and shading performance models. The rooftop photovoltaic system design employed narrow row spacing which produced no shading effects. The ground-mounted system was modelled through a three-dimensional design which used a pitch-to-height ratio of 3:1 to achieve optimal inter-row shading reduction. The floating PV system functioned as an unshaded array which generated water surface reflectivity through a 6% albedo assumption. The thermal modelling used PVsyst' s temperature model which applied a 5°C temperature reduction for the floating PV system to model convective cooling effects. The simulations produced key output parameters which included hourly energy production and performance ratio and capacity factor and detailed system losses.

Table 3: Average Monthly Parameters for The Three Systems for the Year 2020 From PVsyst.

	Average Monthly Irradiance (Wh/m^2)	Average Monthly Power Output GM(kW)	Average Monthly Power Output FPV(kW)	Average Monthly Power Output RPV(Kw)	Average Monthly Array Voltage GM(V)	Average Monthly Array Voltage FPV(V)	Average Monthly Array Voltage RPV(V)	Average Monthly Array Current GM(A)	Average Monthly Array Current FPV(A)	Average Monthly Array Current RPV(A)
January	461.11	84.93	86.54	81.01	635.01	642.18	616.96	132.75	132.44	133.52
February	486.29	89.60	91.32	85.42	634.45	641.82	616.02	139.93	139.59	140.75
March	445.11	81.80	83.31	78.11	635.51	642.56	616.70	127.83	127.53	128.55
April	425.50	77.22	78.63	73.78	635.02	641.89	617.59	120.40	120.12	121.07
May	494.92	91.35	93.10	87.11	636.04	643.49	617.45	142.67	142.33	143.50
June	444.66	81.68	83.22	77.94	633.34	640.39	615.58	127.55	127.25	128.28
July	460.75	84.52	86.11	80.65	634.07	641.22	616.07	132.05	131.74	132.81
August	490.55	89.95	91.70	85.72	633.29	640.66	614.85	140.85	140.51	141.68
September	449.29	82.86	84.44	79.02	633.37	640.46	615.52	129.53	129.22	130.28
October	441.34	81.40	82.90	77.73	635.29	642.32	617.52	126.86	126.86	127.57
November	455.53	83.89	85.46	80.09	635.19	642.33	617.21	130.89	130.59	131.63
December	467.22	85.68	87.31	81.74	634.86	642.08	616.74	134.00	133.68	134.77

2.4.1 Performance evaluation metrics

The performance ratio (PR), which represents the overall efficiency of the PV system independent of location and solar resource, is defined as:

$$\mathrm{PR} = \frac{\mathrm{Y}_f}{\mathrm{Y}_r} \qquad (2)$$

where:

Y_f is the final yield, the net AC energy output normalized by installed capacity,

Y_r is the reference yield, representing total in-plane solar irradiation normalized by standard test conditions (STC irradiance of 1 kW/m²).

The Capacity Factor (CF), representing system utilization over time, is defined as:

$$\mathrm{CF} = \frac{\mathrm{E}_{annual}}{\mathrm{P}_{rated}\ x\ T} \qquad (3)$$

where:

E_{annual} is annual energy output (kWh),

P_{rated} is rated power of the system (kW),

T is total hours in a year (8760 hours).

2.4.2 Economic analysis procedure

HOMER Pro software evaluated the economic performance of the PV systems. The techno-economic analysis required importing annual energy output data from PVsyst into HOMER Pro together with system cost parameters which included capital expenditure (CAPEX), replacement cost, operation and maintenance (O&M) cost, and project lifetime.

The levelized cost of energy (LCOE) was calculated as the ratio of the total lifecycle cost of the system to the total energy produced throughout its operational period. Net present value (NPV) was determined by discounting future cash flows based on the project lifetime and assumed discount rate, while the internal rate of return (IRR) was obtained as the discount rate at which the net present value equals zero.

The generated energy analysis assumes that produced energy will replace both grid electricity costs and diesel generator expenses while all economic indicators were calculated using yearly energy savings and system expenses and financial metrics established in HOMER Pro. The integrated approach provides complete assessment results which evaluate technical capabilities and economic performance for every PV system design.

2.5 Simulation Setup in HOMER Pro

The researchers utilized HOMER Pro to perform techno-economic analysis while they used PVsyst technical performance data as input parameters. The annual energy production values derived from PVsyst simulations for each PV configuration were imported into HOMER Pro as the primary generation input. The systems were modelled as grid-connected configurations which used solar energy production to replace costs associated with electricity from the grid and diesel-based power generation. The study assessed economic indicators through lifecycle cost analysis which included levelized cost of energy (LCOE) and net present value (NPV) and internal rate of return (IRR) and payback period. The procedure involved defining system capital costs, operation and maintenance (O&M) costs, project lifetime, discount rate, inflation rate, and degradation rate within the HOMER Pro environment and the software calculated economic metrics through discounted cash flow analysis. The LCOE was calculated as the ratio of the total discounted lifecycle cost to the total discounted energy produced over the project lifetime:

$$LCOE \quad \frac{\sum_{t=1}^{N}\frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N}\frac{E_t}{(1+r)^t}} \qquad (4)$$

Economic input assumptions were:

Table 4: Economic Input Assumptions

Parameter	Rooftop PV	Ground-mounted PV	Floating PV
CAPEX (#/kWp)	560,000	600,000	610,000
OPEX (% of CAPEX/year)	3.0	3.2	3.3
Discount Rate	8%	8%	8%
Inflation Rate	3%	3%	3%
Project Lifetime	25 years	25 years	25 years
Degradation rate	0.7%/year	0.7%/year	0.7%/year

where:

C_t is the total cost in year t (including CAPEX and OPEX),

E_t is the energy generated in year t (kWh),

r is the discount rate (8%),

N is the project lifetime (25 years).

The economic input parameters used in the analysis are presented in Table 4. The capital expenditure (CAPEX) values were derived from recent market data and literature on PV installation costs in Nigeria and similar developing economies, adjusted to reflect system-specific installation requirements such as mounting structures and floating platform costs. Operation and maintenance costs were assumed as a percentage of CAPEX based on industry standards, while financial parameters such as discount rate and inflation rate were selected in line with typical values used in energy project evaluation studies. Sensitivity analysis was performed by varying CAPEX and discount rate by ±10% to assess the robustness of the results under different economic scenarios.

2.6 Modeling Assumptions and Limitations

All PV system configurations were modelled using the same meteorological data and identical component specifications to ensure that any observed differences in performance were solely due to the installation techniques. The floating PV system included thermal and optical effects that enhanced convective cooling and increased water surface reflectivity. The study excluded grid-related factors, including transmission losses and curtailment events, to make the analysis easier to understand. Economic parameters were derived from International Energy Agency (IEA, 2023) benchmarks and modified to match the specific cost structures and logistical factors of the Nigerian market. The assumptions necessary for maintaining comparative consistency create boundaries that limit our ability to accurately represent actual operational challenges.

3. RESULTS AND DISCUSSION

3.1. Technical Performance Comparison

The three photovoltaic (PV) system configurations which include rooftop and ground-mounted and floating PV systems were assessed through PVsyst simulation outputs that operated under identical environmental and system conditions. The key performance indicators considered include annual energy yield, specific yield, and performance ratio (PR), as presented in Table 5. The floating PV system produced the greatest yearly energy output of 334 MWh which exceeded the ground-mounted system's 321 MWh and the rooftop system's 294 MWh output according to Table 5. The floating PV system produced 13.6% more energy than rooftop PV systems and 4.0% more energy than ground-mounted systems. Floating PV systems operate at better performance levels because their modules maintain lower temperatures which water bodies underneath them provide for better energy conversion efficiency. The results of this study confirm previous research which showed that floating PV systems perform better when their thermal losses are reduced [7, 12]. The performance ratio values which further verify this trend show floating PV systems achieving the highest PR value of 86% while ground-mounted systems reached 82% and rooftop systems achieved 75% performance. The main reason rooftop systems show lower PR values is because their installation areas experience greater thermal losses and shading impacts. The results of this study match previous research which demonstrates that rooftop PV systems have reduced performance because their orientation is not ideal and they collect excessive heat [13]. The floating modules have the advantage of module temperatures reduced by 9° to 12°C; thereby, the impacts to module power are less.

Table 5: Annual Energy Yield and PR

Installation Type	Energy Yield (MWh/yr)	Specific Yield (kWh/kWp /yr)	PR (%)
Rooftop PV	~294	1,422	~75%
Ground-Mounted PV	~321	1,551	~82%
Floatingp PV	~334	1,618	~86%

3.2. Loss Distribution Analysis

The loss components from PVsyst simulation reports explain the different system performance levels that researchers observed which occurred. Floating PV systems demonstrated their lowest thermal losses at 2.64% while showing almost no soiling losses which ranged between 1% - 2% because their modules maintained constant cooling and their water surfaces experienced less dust buildup. The ground-mounted systems showed moderate soiling losses which reached 5% while their thermal losses estimated at 5.43% matched the standard performance levels observed in open-field environments. The rooftop systems experienced their maximum losses when they reached 4% shading losses and 14.38% thermal losses because surrounding structures blocked airflow and caused partial shading. The PVsyst loss diagram outputs provided the loss values which showed how each configuration lost energy through temperature soiling shading and mismatch losses. Rooftop systems experience higher cumulative losses which lead to their lower energy yield and performance ratio compared to other system designs.

3.3. Economic Performance Analysis

The assessment of PV system economic performance used HOMER Pro to analyze technical data which PVsyst generated. The main economic indicators which were evaluated in the study included capital expenditure (CAPEX) operation and maintenance costs (OPEX) and levelized cost of energy (LCOE) as summarized Table 6. The floating PV system achieved the lowest LCOE of ₦147.41/kWh because it required higher capital investment. The system generates more energy, which enables the system to distribute its lifecycle costs across its complete energy output. The ground-mounted system follows closely with an LCOE of ₦148.12/kWh while the rooftop system exhibits the highest LCOE because of its decreased energy output and increased system waste. The research results support existing studies, which demonstrate that system efficiency and energy production volume decrease LCOE even when initial investment expenses increase [5, 8]. The CAPEX and OPEX values were derived from market-based estimates and literature data for PV installations in similar economic environments which were adjusted to system-specific requirements that included mounting structures and installation complexity. The LCOE values were computed in HOMER Pro using discounted cash flow analysis which included system costs and energy production data and financial parameters throughout the project's duration.

Table 6: Summary of Economic Metrics

Metric	*Rooftop PV*	*Ground-Mounted PV*	*Floating PV*
CAPEX(# Million)	116	125	126
OPEX (# Million)	127	122	122
LCOE (#/kWh)	152.96	148.12	147.41

3.4. Payback Period Analysis

The payback period for each PV configuration, as presented in Table 7, was calculated based the annual cost savings which resulted from using solar energy to replace grid electricity and diesel generator power.

Table 7: Summary of Payback Period

Installation Type	Payback (years)
Rooftop PV	2
Ground-Mounted PV	2
Floating PV	1.99

The results show that all three systems reach payback periods which last about two years although floating PV system achieves slightly better performance. The fast return on investment results because Nigeria has high electricity prices which especially affect commercial users who depend on diesel power because their energy expenses can reach more than ₦150 per kilowatt hour. The floating PV systems generate more electricity which enables them to achieve cost recovery at a quicker rate. The short payback periods depend on local energy pricing conditions which differ across economic situations. The financial viability of PV systems improves when electricity tariffs increase according to studies which show similar trends in their findings [8]. The results show that floating PV systems deliver optimal technical performance together with improved economic efficiency which is followed by ground-mounted systems and rooftop PV systems that provide suitable performance for distributed generation. The combination of PVsyst and HOMER Pro created a complete assessment of both technical and economic factors which allowed for an accurate comparison of the three different PV installation methods.

4. CONCLUSION

The study conducted a full economic assessment of floating, ground-mounted, and rooftop photovoltaic systems. The study used PVsyst to evaluate technical performance and HOMER Pro to assess economic performance. The results demonstrated that installation type significantly influences system performance through its impact on thermal behavior, loss mechanisms, and overall energy yield. Floating PV systems established record annual energy yield at 334 MWh yearly and performance ratio at 86% while ground-mounted systems followed with 321 MWh yearly and performance ratio of approximately 82%. Rooftop systems showed the lowest performance results with 294 MWh yearly output and performance ratio of approximately 75%. The different performance outcomes arise from distinct thermal loss patterns and shading impacts and diverse operational conditions which the PVsyst simulation results showed. Floating PV systems achieved their best economic results through their higher initial costs, which produced the lowest levelized energy cost of ₦147.41 per kilowatt-hour and the quickest payback time of about two years. Ground-mounted systems provided a competitive alternative with similar economic performance, while rooftop PV systems were less economically attractive because they produced less electricity and experienced greater system failures. The combined use of PVsyst and HOMER Pro allowed for a complete evaluation of technical aspects and financial results. The research results show that floating PV systems provide the best combination of energy efficiency and cost savings for matching environmental and economic conditions, while ground-mounted systems remain suitable for places with available land and rooftop systems function as effective options for local energy generation.

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