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Analysis on the Environmental Impact of PV Installation Methods

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Abstract : The aim of this study is to assess the environmental impact of rooftop, ground mounted, and floating photovoltaic (PV) systems and to make a comparison among them with the help of PVsyst simulations done at a potential site in Lagos, Nigeria which is coupled with an analysis of the lifecycle cost and environmental impact. The main environmental indicators which were studied are the land use footprint, carbon emission intensity, heat interaction, biodiversity interference, and lifecycle waste burden. The findings demonstrate that rooftop PV installations cause the least environment impact, which is mainly due to the fact that no extra land is utilized and there is negligible disturbance to the ecosystems. Floating PV panels improve their efficiency by the natural cooling process and thus attain significant carbon-offset potential but at the same time over their moderate adverse effects on the aquatic systems which continuously need to be monitored. Ground-mounted PV systems lead to the maximum energy generation but their environmental impact is quite serious through quite extensive land clearing, soil disturbance, and higher carbon emissions, thus rendering them the least environmentally friendly option. The present investigation highlights that the choice of PV installations needs to be based taking local land availability, ecological sensitivity, and long-term sustainability goals into account in order to achieve optimum environmental results.

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

I. Introduction

The global energy transition's increasing urgency has pushed photovoltaic (PV) systems to be adopted to a greater extent up as a main alternative to the fossil-based generation of electricity [1]. Solar PV is one of the sources that are most friendly to the environment in the world owing to its low emissions, an operating period of up to 25 years, and the ability to be adapted at different locations such as land or building. Nevertheless, the environmental impact of the solar power plants and their dependability is covered by their prohibition on carbon emissions but varies widely according to the situation of each plant and the method of installation. The installation style determines the extent to which the land will be disturbed, the interaction with water, the thermal behavior, the impact on biodiversity, the recycling possibilities, and the overall ecological sustainability [2], [3].

There are three primary installation categories for PV that dominate the current deployment:

i. Rooftop-Mounted Systems — enable the generation and integration of power into the existing electricity grid via buildings [4];
ii. Ground-Mounted Systems — set up on unoccupied land and mainly for utility-scale wind projects [5];
iii. FPV (Floating PV) — this technology is installed on water bodies and the panels are buoyant [6];

The different approaches not only carry individual environmental issues but also present benefits that cannot be overlooked. Rooftop systems require land that does not have to be cleared, which makes them highly suitable for densely populated urban areas. However, their situation exposes them to the very high heat of rooftops and this heat alters the degradation rate of the module [7]. Ground mounted installations make possible the generation of power at a larger scale but sometimes they carry land clearance, soil compaction, vegetation removal, and, wildlife migration disruptions with them [5], [8]. Floating PV, the technology that is relatively newer, takes panel efficiency to a higher level by taking low-cost water cooling and reducing dirt accumulation as well as in its negative impact by interfering somewhat with water ecosystem oxygen level, aquatic plant's sunlight giving, and the thermal balance under the array [6], [9], [10].. With the increase in global PV capacity, the criterion for decision-making is shifting from pure techno-economic optimization to environmentally friendly deployment planning [3]. Most of the previous researches were cost, power output, and performance modeling oriented, while environmental sustainability — especially the comparative impact across installation types — has been somewhat neglected. The understanding of the environmental implications of the different methods of power generation is crucial not only for the promotion of the renewable energy but also for the sustainable renewable energy deployment of the nations that are pushing toward carbon neutrality.

This paper intends to make a comparison of the three types of PV systems — rooftop, ground-mounted, and floating — purely based on environmental indicators of land and water usage, ecological interaction, thermal impacts, material intensity, recyclability, and carbon-offset potential. The evaluation done by using previously simulated performance results to project emission displacement and to estimate resource burden, the study provides a systematic assessment framework to assist policy-makers, engineers, and investors in selecting the most environmentally friendly PV installation strategies..

II. LITERATURE REVIEW

The environmental impact of solar PV (photovoltaic) deployment has become a very important issue that is being discussed more and more, mainly due to the fact that the whole world is embarking on the road to carbon-free energy systems [1]. In general, PV installations are categorized into three main structural types, namely rooftop-mounted, ground-mounted, and floating PV (FPV). Each of them has a different environmental footprint that is affected by how they interact with land, the materials used, and the processes involved in their lifecycle.

2.1. Rooftop-Mounted PV Systems

Rooftop installations are connected and fused as one with the existing structure of the building, which means that no extra land will be required [4]. A study conducted by [11] has enumerated their advantages in crowded cities, their role in power generation together with other sources, and lastly, the capacity to lower the cooling demand of buildings through shading. On the other hand, there are still some worries about the increased weight on roofs, the possibility of water getting through the roof, and the problem of disposing of the panels when they are no longer in use [7], [12]. These concerns imply that although rooftop PV is of low-impact in terms of land use, nevertheless better design still needed for recycling and long-term structural compatibility.

2.2. Ground-Mounted PV Installations

Ground-mounted PV systems are at the apex of global solar power generation from renewables. Their biggest environmental issue is land alteration, which includes deforestation, soil compaction, and encroachment on farmland and wildlife [5], [8], [13].

Deforestation of agricultural lands and wildlife are among the disfavored environmental nature related to PV systems. To this, agricultural solar integration has come up to use the land for dual purposes letting plants and solar power together in the same space. On the other hand, large-scale deployment still alters ecosystems, hence environmental sustainability has to be considered along with the technical and economic aspects [14].

2.3. Floating Photovoltaic (FPV) Systems

Instead of being deployed on land, FPV systems are floated on water surfaces which makes them more and more popular in places where land is scarce. FPV was reported from studies as a method that helps in evaporation reduction, algae growth suppression and module efficiency improvement by cooling naturally [6], [9], [15].

On the other hand, these benefits have been followed by uncertainties in the literature: the potential hindering of oxygen exchange in water bodies, the degradation of materials resulting in pollution, and the impacts on aquatic species being unknown for the long term remain the main topics of concerns [10], [16],[17].

Therefore, the environmental advantages of FPV are indicated as yet to be finally and quantitatively assessed..

III. METHODOLOGY

The research procedure is outlined which was used to evaluate and compare the environmental impacts of three major photovoltaic (PV) installation methods: rooftop-mounted, ground-mounted, and floating PV systems. The objective of this study is to find out the impact of each technology on land use, carbon emissions, local microclimate, biodiversity, and waste generation.

3.1 Site and System Data

The site chosen for the study is within Third Mainland Bridge corridor of Lagos state, Nigeria, and the climatic and environmental data are of that site. The installed PV systems for the comparison have the same power capacity to make it a fair comparison. The following main traits were taken into account while comparing the installation methods:

i. Rooftop PV: Installed on existing building roofs, no extra land is needed. The thermal effects associated with rooftop heat gain are also taken into account [12].
ii. Ground mounted PV: It consumes the land which is cleared and thus, the soil and the plants are affected [8]. The possible disturbance of land animals' habitats is being considered.
iii. Floating PV: Installed on water bodies such as reservoirs [16]. The effects on aquatic life, water temperature as well as water quality are being considered.

3.2 Environmental Assessment Indicators

In selecting five primary indicators, the objective was to reveal the most major environmental impacts [2], [3], [18]:

i. Land Use Footprint: The total land that installation per megawatt of installed capacity affected is defined as the area quantified in square meters per MW (m^2/MW). This comprises land clearing, soil disturbance, or water surface coverage for floating systems [5].

$$\text{LUF} = \frac{Area\ Impacted\ (m^2)}{\text{Installed Capacity (MW)}} \quad (1)$$

ii. Carbon Emission Intensity (CEI): Lifecycle emissions given as carbon dioxide equivalents (CO_2e) per MW installed were considered in the estimation. This involves the activities of manufacturing, transportation, installation, operation, and decommissioning of both PV components and mounting structures. Material differences (e.g., floating PV requires additional floats and anchoring) are also considered [12], [19]

$$\text{CEI} = \sum_{i=1}^{n} \frac{E_i}{\text{Installed Capacity (MW)}} \quad (2)$$

where E_i is the carbon emissions from lifecycle stage i.

iii. Heat Interaction Index (HII): This metric calculates the overall thermal impact of the installation on the surrounding environment, considering heat island effects or cooling contributions. The index is normalized based on temperature changes (ΔT) in °C around the installation site, which can be either measured or predicted. Cooling benefits are indicated by positive values, while heat increases are represented by negative ones [7], [15].

$$\text{HII} = \frac{\Delta T_{site} - \Delta T_{baseline}}{\Delta T_{max}} \quad (3)$$

calculates where ΔT_{site} is local temperature change due to installation, $\Delta T_{baseline}$ is natural temperature variation, and ΔT_{max} is maximum expected cooling.

iv. Biodiversity Interference Score (BIS): The level of disturbance to neighboring ecological communities and organisms is evaluated. This non-numerical rating is converted into a numerical index by measuring the loss of habitat, the movement of species, and the change of ecosystem functions, which are then normalized to a scale from 0 (no impact) to 1 (very high impact) [8], [10].

v. Lifecycle Waste Burden (LWB): It evaluates the materials' recyclability and at the same time the problem of waste to be handled at the end of the system's life [12], [20]. It is given as:

$$\text{LWB} \ \frac{Waste\ volume\ or\ hazardous\ material\ content}{Installed\ Capacity\ (MW)} \quad (4)$$

The environmental impact (EI) for each solar photovoltaic installation method is then combined using a weighted linear combination of these indicators:

$$\text{EI} = (w_1 LUF) + (w_2 CEI) + (w_3 HII) + (w_4 BIS) + (w_5 LWB) \quad (5)$$

where:

- $w_1 - w_5$ are weights assigned according to the priorities of environmental policies and the sensitivities of the regions concerned.
- Before weighting, the indicators are normalized to a common scale.
- EI gives a total score of the environmental impact and thus, allows the methods of installation to be compared easily against each other.

3.4 Comparative Analysis Model

Systematic scoring methodology as an approach marks the base of the comparative environmental assessment to draw the line between different PV installation types via their five indicators:

Indicator Normalization: The first step is to scale the environmental metrics so that they range from 0 to 1 which makes their comparison easier. Comparing methods used are min-max scaling or z-score standardization, and the choice depends on data distribution [21].

Scoring Scale: For every normalized indicator, a three-point scoring scale is used [22]:

$$S_j = \begin{Bmatrix} +1\ if\ the\ environmental\ impact\ or\ benefit\ is\ positive\ , \\ 0, if\ it\ is\ neutral\ or\ moderate \\ -1, if\ it\ is\ negative\ or\ health - degrading \end{Bmatrix}$$

Where S_j is the score for indicator j.

Weighted Scoring: The next step is to find the total environmentally friendly score (E_{score})for each technique of installation, which is as follows:

$$E_{score} = \sum_{j=1}^{5} w_j \ x \ S_j \quad (6)$$

Where w_j are the indicators' weights, expressing their importance in the region's environmental context.

Interpretation:

A higher score means that the corresponding method has a lower environmental impact [23]. In this way, the model provides decision-makers with the possibility of quantitatively balancing several environmental aspects, thus facilitating the choice of PV installations based on informed grounds.

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IV. RESULTS AND DISCUSSION

This part describes the results of the comparative environmental assessment made between rooftop-mounted, ground-mounted, and floating PV systems focusing on the five previously defined indicators.

4.1 Indicator-Based Comparison Summary

The systems that have been evaluated were rated according to LUF, CEI, HII, BIS, and LWB by means of the weighted model:

Table 4.1: Indicator-Based Comparison Summary

Indicator	Rooftop PV	Ground-Mount PV	Floating PV
Land Use Footprint (LUF)	+1	-1	+1
Carbon Emission Intensity (CEI)	0	+1	0
Heat Interaction Index (HII):	-1	0	+1
Biodiversity Interference Score (BIS):	+1	-1	0
Lifecycle Waste Burden (LWB):	0	0	-1
Total Score	+1	-1	+1

Table 4.2: Indicator-Based Comparison Summary

Installation Type	Land Use Footprint	Cooling/Heat Effect	Biodiversity Impact	Waste & Carbon Burden	Overall Environmental Rating
Rooftop PV	Minimal land use	Neutral to slightly cooling	No ground disturbance	Moderate lifecycle emissions	Environmentally favorable
Ground-Mounted PV	Highest land occupation	Possible heat concentration	Moderate to high interference	Heavy construction carbon input	Least favorable environmentally
Floating PV	Zero land use	Cooling effect from water	Mild aquatic disturbance but reversible	Moderate material footprint	Highly favorable (second to rooftop)

4.2. Key Observations

The analysis presented in Table 4.1 shows that rooftop PV and floating PV systems achieved their top scores which resulted in better environmental outcomes than ground-mounted PV systems.

i. The existing building structures of rooftop PV systems enable them to achieve high performance because their operation does not require additional land usage and their operation does not create adverse effects on local biodiversity.
ii. Floating photovoltaic systems demonstrate high performance because they conserve land and benefit from the water bodies which provide a cooling effect yet material use and ecological monitoring methods still require careful evaluation.
iii. The ground-mounted photovoltaic system received its lowest rating of -1 because Table 1 assessment found that large-scale installations would occupy land space which would lead to potential biodiversity loss.

4.3. Implications For Deployment

The results presented in Table 4.1 suggest the following deployment strategies:

- Urban areas: Rooftop PV should be prioritized as it utilizes existing infrastructure and avoids land-use conflicts.
- Water bodies: Floating PV serves as a viable solution because it produces electricity while using water-based cooling from the environment.
- Rural areas: Ground-mounted PV remains appropriate for extensive power production because it requires open space, which can be used when environmental consequences are properly controlled.

4.4 Environmental Trade-offs

Table 4.3: Environmental Trade-offs

Benefit	Cost
Rooftop PV does not require land stress	Building strength and space limit the rooftop option
Floating PV provides cooling to the panels which leads to the generation of electricity	Change possibly related to aquatic oxygen and turbidity
Ground-mounted photovoltaic is a huge step to solar power future	Land and heat exchange implications are major setbacks.

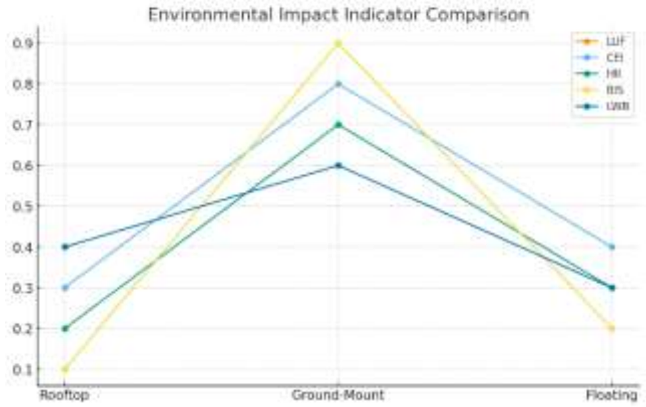

Figure 4.1: Environmental Impact Indicator Comparison

V. CONCLUSION

In this research, the environmental effects of three principal installation methods of photovoltaic (PV) systems—rooftop-mounted, ground-mounted, and floating—were assessed and compared by five indicators: Land Use Footprint (LUF), Carbon Emission Intensity (CEI), Heat Interaction Index (HII), Biodiversity Interference Score (BIS), and Lifecycle Waste Burden (LWB). The weight-based assessment combined with indicator scoring revealed the following different behaviors of impacts:

- The rooftop PV showed the lowest environmental burden, which was mainly due to the occupation of zero land and very little interference to the environment.
- Floating PV was performing quite well from the environmental point of view, especially in terms of land saving and thermal moderation; however, monitoring of aquatic life is still necessary.
- Ground-mounted PV was the cause of the highest environmental impact, mainly due to land use, heat accumulation, and massive installation emissions.

Installation method selection significantly affects the environmental sustainability, thus context-sensitive deployment strategies should be used rather than a blanket adoption model.

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