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Perspective

Accelerating the Low-Carbon Energy Transition in Sub-Saharan Africa through Floating Photovoltaic Solar Farms

Tarelayefa Igedibor Ingo [1,*], Louis Gyoh [1], Yong Sheng [2], Mustafa Kemal Kaymak [3], Ahmet Duran Şahin [4] and Hamid M. Pouran [1]

[1] Faculty of Science & Engineering, University of Wolverhampton, Wolverhampton WV1 1LY, UK; l.gyoh@wlv.ac.uk (L.G.); h.pouran@wlv.ac.uk (H.M.P.)
[2] School of Engineering, Hull University, Hull HU6 7RX, UK; y.sheng@hull.ac.uk
[3] Sustainable Energy and Climate Systems Laboratory, Energy Institute, Istanbul Technical University, Maslak, 34469 İstanbul, Türkiye; kaymak@itu.edu.tr
[4] Sustainable Energy and Climate Systems Laboratory, Meteorological Engineering Department, Aeronautics and Astronautics Faculty, Istanbul Technical University, Maslak, 34469 İstanbul, Türkiye; sahind@itu.edu.tr
* Correspondence: t.i.ingo@wlv.ac.uk

Abstract: Climate change has become a global issue and is predicted to impact less-developed regions, such as sub-Saharan Africa, severely. Innovative, sustainable renewable energy systems are essential to mitigate climate change's effects and unlock the region's potential, especially with the increasing energy demands and population growth. The region relies heavily on fossil fuels, which calls for urgent action towards energy security and expansion. Hybrid floating solar photovoltaic-hydropower (FPV-HEP) technology has emerged as a cost-effective and transformative solution to accelerate the low-carbon energy transition in sub-Saharan Africa. The technology combines solar panels with existing hydropower infrastructure, ensuring energy security while reducing carbon emissions. This technology offers several benefits over conventional ground-mounted solar systems, including efficient land utilization, energy generation, and water conservation. However, its adoption remains challenging due to technical complexities and evolving regulatory frameworks. Despite these challenges, Nigerian energy professionals have preferred renewable alternatives, mainly distributed solar PV and FPV-HEP plants. This collective embrace of FPV and renewables reflects a growing understanding of their critical role in mitigating climate change through sustainable energy practices. This research aims to contribute to the existing body of knowledge and assist policymakers in making informed decisions on adopting this technology. It also stimulates further research on this topic, offering a new potential solution to the ever-increasing demand for green energy in the region to meet their sustainable development needs.

Keywords: sub-Saharan Africa; climate change; decarbonization; energy transition; floating solar; innovation; hybrid floating solar photovoltaic-hydropower

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1. Introduction

Globally, energy is one of the main drivers of nations' economic and social development. Africa's installed renewable electricity capacity was about 53.4 GW in 2020, with a total renewable electricity generation of around 173 TWh/year in 2020 [1,2] The continent is also blessed with abundant sunshine year-round, with solar irradiance levels exceeding 2000 kWh/m^3. However, access to modern energy services and electricity is at a low herb in many developing countries, especially in sub-Saharan Africa, such as Nigeria, and parts of Asia [3–5], indicating that much renewable potential is yet to be exploited. Despite this, about 90% of electricity generation in countries such as Ethiopia, Malawi, Mozambique, Namibia, and Zambia is supplied by hydropower [6]. However, increasing levels of frequent droughts in recent decades have adversely affected the output of these hydropower systems [7].

About 64% of Africans rely predominantly on gathered wood and agricultural and animal waste as cooking fuel, accounting for over 40% of the total increase in final energy use between 2010 and 2019 [1]. Moreover, it is known to have adverse environmental and health effects. This scenario calls for expanding access to reliable, affordable, and clean/low-carbon modern energy, and technological innovation is crucial in this regard. Accelerating the transition to clean energy technologies is critical to that transformation in the face of persistent increases in energy demand [8].

According to the International Renewable Energy Agency, commercially available low-emission innovations have the most significant potential to reduce GHG emissions by 2030 and beyond. The International Renewable Energy Agency [9] describes the energy transition as transforming the energy sector from fossil-based to net-zero carbon by 2050. Transitioning to net-zero emissions means finding sustainable ways to solve all the problems we currently solve with fossil fuels. Transition to a low-carbon economy is essential for ensuring that global warming is kept well below the 2 °C limits by 2050, as per the 2015 United Nations Framework Convention on Climate Change (UNFCC) Paris Agreement, and to limit it to the recently agreed 1.5 °C by governments and stakeholders at the conference of the parties, COP26 [10].

A prosperous, equitable, and lasting shift towards clean energy relies on implementing innovative solutions. The resultant impact is mitigating climate change while improving energy security. Access to more efficient technologies, products, services, or business models helps achieve innovation in various markets, societies, and governments. The energy sector requires considerable time for innovations to develop and spread, and it is challenging for low-carbon innovations to gain traction due to the "carbon lock-in" effect. Carbon lock-in refers to the self-perpetuating inertia of large fossil fuel-based energy systems that restrains public and private efforts to introduce alternative technologies [11]. The current energy infrastructure needs to be transformed to address the challenges posed by global climate change. Achieving emissions reduction at scale would entail implementing innovative approaches that leverage existing technologies.

The technological innovation process for a low-carbon economy is complex and dynamic and can be slow. It comprises five stages: research and development (R&D), applied R&D, demonstration, market development, and commercial diffusion [9,12]. Each stage also includes feedback loops, offering insights into gaps or opportunities.

Figure 1 compares the progression pathways of two solar technologies originating in Africa—the developing floating photovoltaic (PV) and the established ground-mounted solar PV. The diagram illustrates the various stages of development these technologies go through, from their invention to their diffusion in the market. Two primary dynamics support these stages: 'Market Pull' and 'Technology Push'. The 'Market Pull' dynamic refers to technological development in response to the demand and requirements of consumers and the market. At the same time, the 'Technology Push' is characterized by innovation driven by research and development (R&D) efforts.

The figure also highlights the critical interaction between market incentives and R&D in driving the growth and assimilation of solar technology within the African energy sector. It underscores the necessity for consumer demand and continuous R&D endeavors to effectively launch and embed emerging technologies like floating solar PV into the market. This concept is visualized through the depiction of each phase being simultaneously driven by market preferences and technological innovation, necessitating a foundational stream of basic and applied R&D.

In contrast, ground-mounted solar PV is portrayed as a technologically mature entity with momentum derived mainly from existing market demand. The illustration implies that such mature technologies have already traversed the preliminary stages of innovation and are now firmly situated in the diffusion phase, where market forces predominantly catalyze their expansion.

During the commercial diffusion phase, the focus shifts towards building industrial capacities around technologies that have been proven effective in the market formation phase of the technology innovation value chain. As innovation progresses, its costs typically increase throughout its life cycle, meaning that even a smaller proportion of "push" efforts may still require higher financial support.

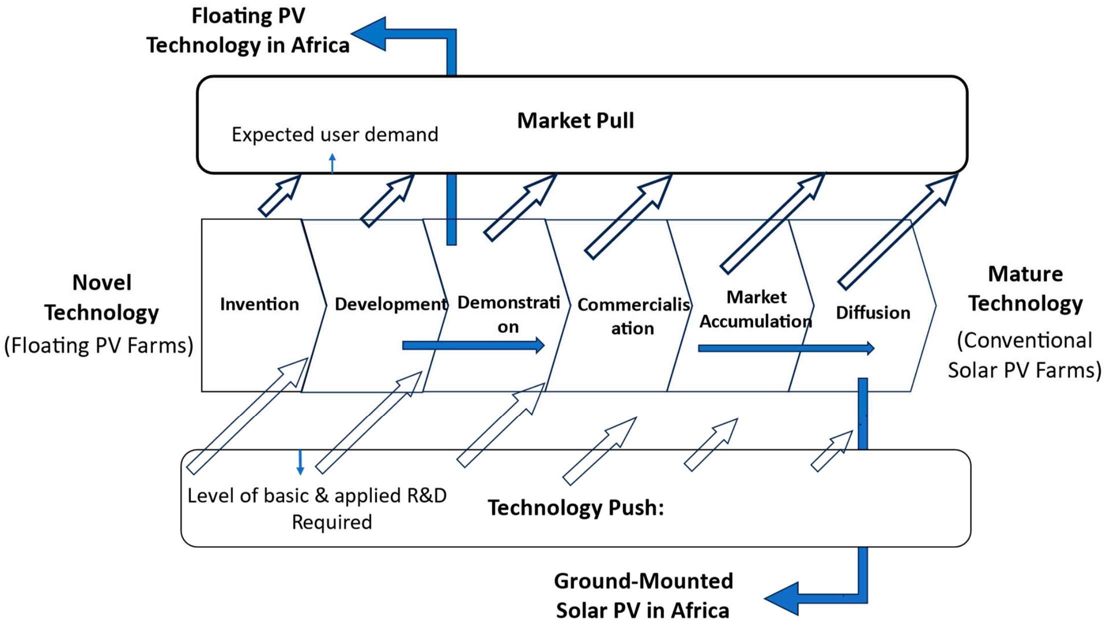


Figure 1. Innovation life cycle showing the progression pathways of floating photovoltaic (PV) and ground-mounted solar PV technologies in Africa.

Table 1 offers a roadmap for renewable energy technologies in sub-Saharan Africa, tracing their evolution from developing ideas to widespread market integration. The process begins with the research and development (R&D) phase, where new concepts like localized floating photovoltaic (FPV) systems take root. Here, securing adequate funding and building technical expertise become the primary hurdles. As the technology progresses to the market formation stage, the focus shifts to overcoming market barriers and inconsistent policies that impede its adoption, paving the way for broader acceptance. Finally, the commercial diffusion stage marks the pinnacle, where established technologies like FPV can be scaled up for broader implementation. However, challenges persist at this stage, including inadequate infrastructure, financial limitations, and the complexities of integrating these technologies into existing power grids.

Table 1. Stages of innovation in renewable energy technologies in sub-Saharan Africa.

Innovation Stages	Description	Example	Challenges	References
Research and Development (R&D)	- Developing new renewable energy technologies	- Initial research into localized FPV systems	- Limited R&D funding and technical expertise	[8,9]
Market Formation	- Preparing the market for new technologies	- Scaling up solar PV projects	- Market barriers - Policy inconsistency - Lack of consumer awareness	[8,12]
Commercial Diffusion	- Widening adoption of mature technologies	- Integration of FPV systems with existing hydropower	- Infrastructure deficits - Financing challenges - Grid integration issues	[1,8]

(Source: Author).

Renewable energy holds immense promise for sub-Saharan Africa [13], with abundant solar resources exceeding 2000 kilowatt-hours per square meter (kWh/m^2) in many areas and significant hydropower potential. However, the region faces a stark gap between this potential and actual deployment. Key issues impeding progress include the following:

Inadequate infrastructure: The need for efficient transmission and distribution networks limits the integration of and delivery of renewable energy to consumers.

Inconsistent policies: Unstable regulatory frameworks and a lack of long-term policy commitments create uncertainty for investors and hinder market formation.

Limited financing: Access to affordable capital remains a significant challenge, particularly for early-stage technologies and large-scale infrastructure projects.

These challenges are particularly evident in solar energy, despite its high potential. Low deployment rates can be attributed to a combination of factors, including a lack of adoption strategies, inconsistent policy frameworks, and limited access to financing and technology. Similarly, hydropower, while offering significant potential, faces challenges related to its dependence on consistent water flows, the impacts of climate-induced droughts, environmental and social concerns, and financial uncertainties faced by utilities and policy frameworks [14].

Understanding these crucial stages and their associated hurdles, along with the broader challenges impeding renewable energy expansion, is vital for supporting innovation in sub-Saharan Africa. A brighter future powered by clean and sustainable energy can be achieved by addressing these barriers, fostering innovation across the technology lifecycle, and harnessing the region's abundant renewable resources. This perspective paper discusses the central role of innovation in the transition to a low-carbon economy in sub-Saharan Africa, with a focus on floating solar farms, which is an emerging technology. We discuss low-carbon innovation approaches to floating solar photovoltaics (FPV) and hybridized FPV–hydropower technologies and their potential contribution to resolving the energy security challenge and reducing emissions. We also look at the possible barriers to its deployment in sub-Saharan Africa.

This paper aims to enhance understanding of the potential role of floating solar farms as an emerging technology in sub-Saharan Africa. It reflects on the advantages of hybridizing floating PV with existing hydropower plants and highlights the practical implications of these findings. Discussing the less explored topic of this technology in the context of sub-Saharan Africa aims to stimulate stakeholder interest in its adoption. The SWOT analysis presented in this study and the discussion of implementation challenges and barriers provide decision-makers with a clear understanding of the feasibility of deploying this nascent technology. It also briefly describes the perception of energy professionals about the role of this technology in the region, setting the stage for more detailed discussions in follow-up papers.

The paper is structured as follows: A Methodology Section (Section 2) presents the methodology approach adopted for this work, which involves a desktop-based study through a review of pertinent literature that informed the theoretical basis and data collection instrument using a survey questionnaire. Section 3 discusses advancing sub-Saharan Africa's energy transition with innovative floating solar farms. Section 4 presents stakeholders' perspectives on floating solar farms, renewable energy adoption, and decarbonization strategies in Nigeria, as well as some case studies of FPV-HEPP applications in similar regions worldwide in the Section "Some Case Studies of FPV-HEPP Applications". Section 5 discusses the advantages, implementation challenges, and barriers to deploying FPV–hydropower systems in sub-Saharan Africa, while Section 6 presents a SWOT analysis of hybrid floating solar PV–hydropower systems. Limitations to the study are captured in Section 7. Finally, the Conclusion, Section 8, gives a summary of the main findings.

2. Methodology

This perspective paper incorporates desk-based studies for a theoretical foundation, systematic data evaluation for empirical analysis, and expert analysis models to better understand deploying floating solar farms in sub-Saharan Africa, particularly Nigeria. The emphasis on hybrid FPV technology is due to sub-Saharan Africa's unique geographical advantages, such as high solar irradiance and the extensive network of hydropower reservoirs and dams that are primarily grid-connected. The deployment of hybrid FPV–hydropower systems, as revealed by this study, could significantly contribute to the diversification of the renewable energy mix, aiming to surmount the region's challenges of energy insecurity and thereby revolutionizing the energy sector in Nigeria. In addition to the above, this study provides primary data collected through a survey methodology, encompassing responses from 101 professionals across various sectors related to energy in Nigeria. The selection of participants was purposive, targeting a diverse group of stakeholders from the energy sector, academia, government regulatory agencies, and independent energy consultants. These participants were asked for expert perspectives on the most appropriate renewable energy technologies (RETs) or their combinations for providing clean, sustainable, reliable, and affordable electricity in Nigeria.

3. Advancing Sub-Saharan Africa's Energy Transition with Innovative Floating Solar Farms

The transition towards a low-carbon economy in sub-Saharan Africa encounters significant hurdles, primarily due to the persistent "carbon lock-in" effect. This phenomenon signifies the entrenched reliance on extensive fossil fuel-based energy infrastructures, which inherently discourages the adoption of alternative, more sustainable energy technologies. Such systemic inertia presents formidable innovation barriers, often termed "innovation gaps" [15,16].

Innovation gaps are critical technological challenges that must be surmounted to foster research, development, and deployment (RD&D) conducive to a clean energy transition. A notable obstacle in this journey is the "valley of death," a phase in the innovation cycle where promising pre-commercial technologies struggle to secure the necessary investment to achieve commercial viability. Overcoming this phase requires finding a willing adopter to navigate the technology-specific barriers. Figure 2 is a graphical representation of the innovation adoption lifecycle, particularly as it applies to the diffusion of new technologies like floating PV (photovoltaic) farms. It depicts the typical journey from the initial adoption of an emerging technology to its full commercialization and acceptance within the market. The graph comprises a bell curve divided into segments representing different technology adoption stages. The "diffusion chasm" represents the critical juncture where targeted strategies can propel the technology past the tipping point towards broader acceptance.

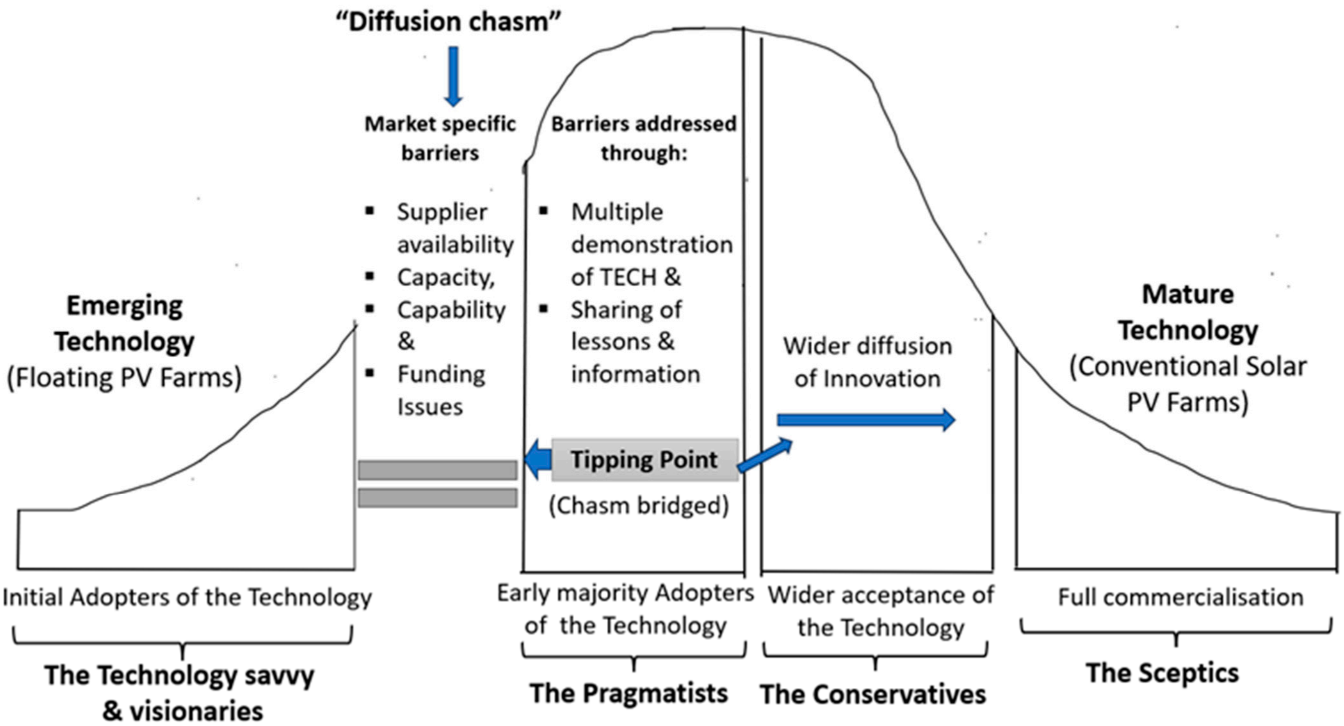


Figure 2. Innovation adoption lifecycle for floating PV farms (Source: Author).

Despite these barriers, the global community increasingly recognizes solar energy, particularly solar panel technology, as a feasible solution to these challenges. However, traditional solar farms require significant land, a scarce resource in many regions. This limitation has led to the innovative development of "floatovoltaics", or floating solar photovoltaics (FPVs), where solar panels are mounted on buoyant structures and deployed on water bodies like reservoirs and lakes [17]. Since the first over 1 MW scale FPV installation in Japan in 2013, the technology has seen rapid adoption, particularly in countries such as Japan, China, and the USA, making it one of the fastest-growing renewable energy technologies [17–19]. Figure 3 shows a schematic representation of a floating solar farm adapted from [20]. It also shows a hydropower-integrated floating solar farm in Portugal (photo credit Energias de Portugal, www.edp.com (accessed on 13 February 2024).

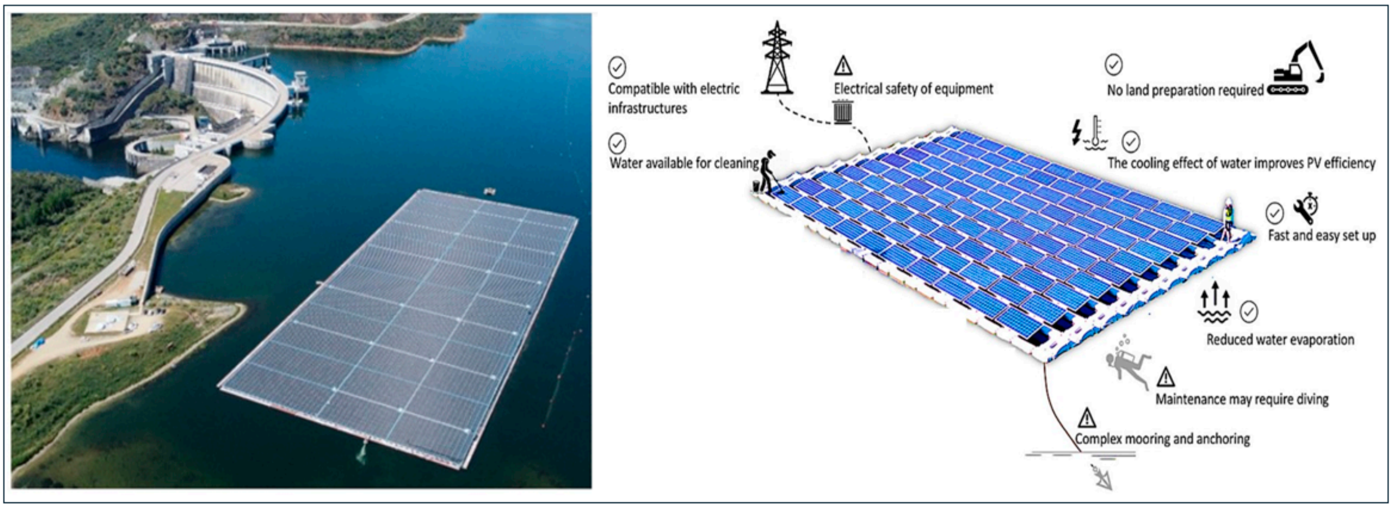


Figure 3. A schematic representation and photo of a hybrid floating solar PV–hydropower system (photo credit for hydropower integrated floating solar farms: Energias de Portugal).

In Africa, where hydropower is the primary renewable energy source yet hampered by accessibility, integrating floating photovoltaic (FPV) systems with existing hydro infrastructure emerges as a promising and economical innovation. This hybrid floating solar PV—hydropower system conserves land and enhances the efficiency of hydropower operations by curtailing water evaporation. Thanks to the declining costs and advances in solar PV technology, FPV is becoming a formidable contender in the energy sector. This paradigm shifts towards FPV, driven by land use efficiency, energy security, climate goals, and resilience, as evidenced by the substantial rise in global FPV capacity, escalating from a mere handful of megawatts in 2017 to a projected 3000 MW by 2021 [18,21]. Such expansion highlights FPV's role in addressing energy deficits and bolstering climate change resilience, reducing the necessity for expansive new infrastructure. A modest application of FPVs could significantly amplify Africa's hydropower capacity, directly confronting the continent's energy scarcity and climatic adversities.

Hydropower's global significance as a renewable resource is incontrovertible, with a 1307 GW capacity contributing 16% of the world's electricity in 2018 [14]. However, the viability of hydropower is susceptible to the impacts of climate-induced changes in hydrological patterns, potentially diminishing its output, especially in arid regions prone to climate change's harsher manifestations, like severe heatwaves and droughts. The advent of FPVs offers a strategic complement to traditional hydropower, adaptable to various aquatic settings, including dam reservoirs. Retrofitting dams with FPVs bolsters the total energy production by harnessing solar power, thus optimizing the existing electrical grid and maintenance frameworks. Additionally, the water's cooling effect improves solar panel efficiency [22,23]. The world's first grid-connected FPV–hydroelectric system at Portugal's Rabagão Dam in 2016 exemplifies this synergy, enhancing energy provision without the need for new dams, as corroborated by studies on Brazilian dams (Sulaiman et al., 2021). Incorporating FPVs into hydropower schemes promises increased reliability and flexibility, particularly during peak demand, and is expected to double installed capacity while conserving water resources [17,24]. Though uncertain, the projected global potential for FPV–hydropower hybrids are considerable, estimated between 3.0 and 7.6 TW [25].

With Africa's hydropower dams serving as the largest renewable energy source for a population where access to electricity is less than 50%, the FPV–hydropower integration represents a strategic allocation of PV plants that align with ecological preservation and increased generation capacity. Not only can FPVs mitigate reductions in hydropower output during dry spells, but they also offer a resilient response to climate change without intensive infrastructural overhauls. Floating solar PV installations could double Africa's hydropower capacity, significantly elevating electricity generation from 28 GW to 58 GW with just a 1% coverage of reservoirs by solar panels [26]. This expansion is vital to consider the substantial untapped hydro resources and the socio-political and environmental challenges associated with new dam construction.

Considering pressing energy poverty and climate change impacts, such as disrupted hydrological cycles, FPVs present a sustainable avenue to enhance the continent's energy infrastructure.

Moreover, the technology's integration with over 50 dams currently under construction across Africa underscores its potential as a renewable solution to the continent's burgeoning energy demands. Figure 4 depicts the solar resource map for Nigeria and sub-Saharan Africa, which reflects the electricity generation potential based on ground-mounted solar potential. The source of this information is the World Bank's Global Solar Atlas 2.0, which has been compiled using SolarGIS solar resource data. (Credit SolarGIS www.solargis.com (accessed on 23 February 2024).

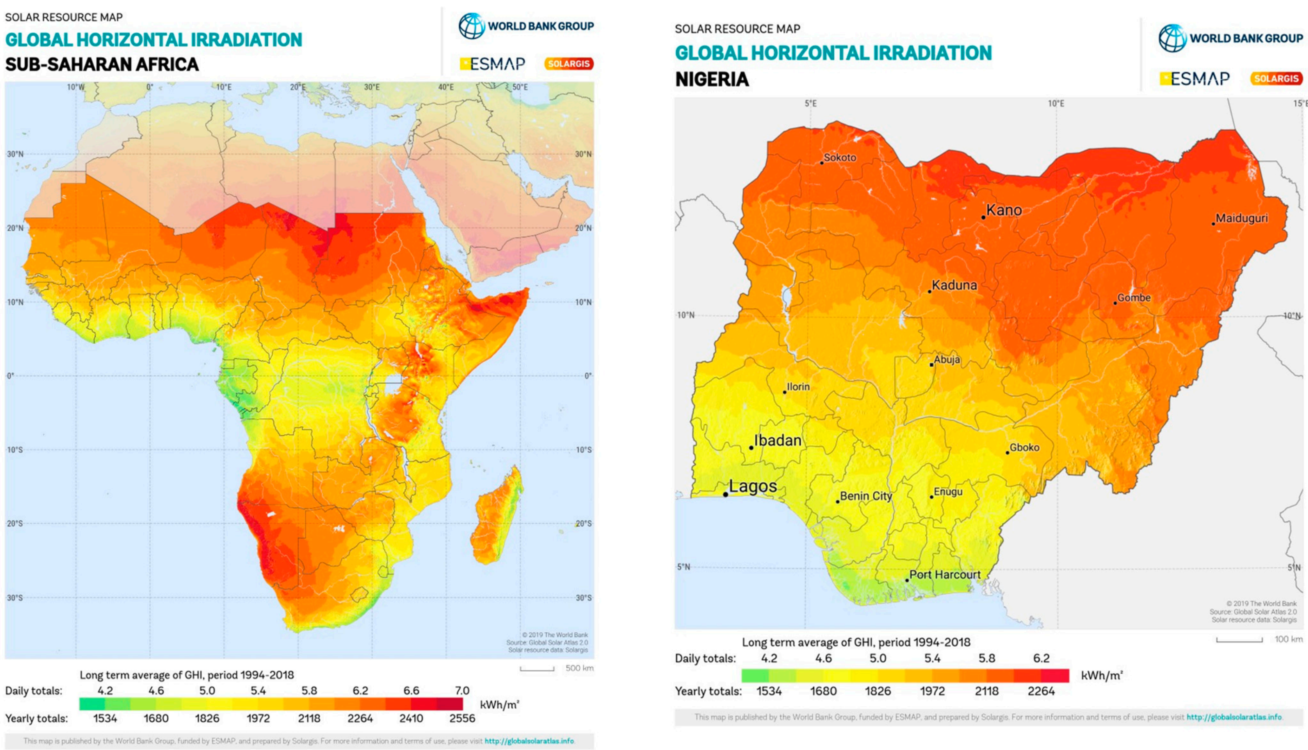


Figure 4. Solar resource map for Nigeria and the entire sub-Saharan Africa (Source: [13]).

4. Stakeholders' Perspectives on Floating Solar Farms and Renewable Energy Adoption, and Decarbonization Strategies in Nigeria

The floating solar photovoltaic (FPV) sector is witnessing growing interest, yet it stands at the early stages of realizing its deployment potential. As stakeholders deliberate on the synergistic benefits of FPVs coupled with hydropower systems, technical potential analysis becomes increasingly relevant. In the merger of solar and hydro operations, hybrid systems reap benefits from their autonomous functionalities. Notably, hydroelectric plants boast established grid connections, simplifying the integration of PV panels and significantly reducing additional infrastructural demands. Table 2 compares the ground-mounted PV and FPV solar farms, reflecting on the advantages of FPVs, particularly in regions where land preservation for agriculture takes precedence, yet abundant water bodies present untapped opportunities for energy harvesting.

Table 2. Comparison of ground-mounted solar PV vs. floating solar PV.

Feature	Ground-Mounted Solar PV	Floating Solar PV (FPV)
Land Use	Requires significant land area, potentially conflicting with agricultural or natural land	Utilizes water surfaces, reducing land use conflicts and preserving valuable land for other purposes
Energy Efficiency	Standard efficiency, can be affected by land conditions and temperature	Potentially higher efficiency due to the cooling effect of water on the solar panels
Water Conservation	No direct impact on water conservation	Reduces water evaporation from reservoirs, aiding in water conservation
Installation Costs	Varies depending on land acquisition and preparation costs	Potentially higher initial costs due to specialized floating platforms and anchoring systems
Maintenance	Regular cleaning and maintenance required; easier access	Maintenance can be more challenging due to the need for waterborne access; panels stay cleaner due to reduced dust accumulation
Environmental Impact	Land alteration and habitat disruption possible; requires careful siting	Limited impact on terrestrial ecosystems; potential impact on aquatic ecosystems needs assessment
Climate Resilience	Vulnerable to climate-related land changes (e.g., erosion, desertification)	Offers resilience against land-based climate challenges; vulnerable to water-level variations and extreme weather
Integration with Existing Infrastructure	Requires new infrastructure or integration into existing land-based grid	Can be integrated with existing hydropower infrastructure, enhancing overall energy output and stability
Suitability for Sub-Saharan Africa	Suitable, but land availability and environmental impact must be considered	Highly suitable due to high solar irradiance and the availability of water bodies; addresses land scarcity issues
Potential for Expansion	Limited by land availability and competing land uses	Significant potential, especially in areas with limited land but abundant calm water bodies like lakes and reservoirs

(Source: Author).

In terms of comparing output efficiency between FPV and GMPV systems, as stated earlier, one of the advantages of floating solar PV technology over ground-mounted solar PV (GMSPV) is the higher energy gain resulting from the cooling effect of water. Ref. [27] in their evaluation of the Tengeh reservoir in Singapore, reported that FPV has a low temperature that ranges between 5 °C and 10 °C lower than the conventional ground-mounted solar PV system. In Bengal, India, comparative studies of FPV and GMPV indicated a 10.2% higher energy output by the FPV [28] (Goswami et al., 2019). Similarly, studies by Choi et al., using data from the FPV facility installed at K-water, were over 11% more efficient than the energy generated by the GMPV system [29]. Also, an assessment of cooled FPV modules by Elissandro et al. in the Castanho, Banabui, and Oros reservoirs in Brazil shows that FPV has an average conversion efficiency of 12.5% higher compared to ground-mounted solar PV systems [30]. The World Bank has also reported an energy gain of 5 to 10%. In the Netherlands [31], also reported a higher % energy output of 6% by FPV compared to GMSPV systems.

To capture stakeholder perspectives on the viability of floating solar technologies within Nigeria, we surveyed 101 participants to expedite the adoption of hybrid floating solar PV–hydropower technology across sub-Saharan Africa, using Nigeria as a focal point. This survey encompassed a broad spectrum of professionals from various sectors, including the energy industry, oil and gas, academia, governmental regulatory bodies, finance, energy analysis, geoscience, NGOs, research institutions, governmental water agencies, and independent consulting within Nigeria. Participants were asked to select their top three renewable energy technologies (RETs) or combinations thereof that they believe are most suited for delivering clean, sustainable, reliable, and affordable electricity in Nigeria, particularly emphasizing off-grid rural and coastal areas currently underserved. The results (Figure 5) revealed that 60% of the respondents advocated for distributed solar PV systems as the ideal RET for Nigeria, indicating a strong preference for small-scale, decentralized energy solutions. Following closely, 57% supported integrating hybrid floating solar–hydropower systems, and 53% saw the large-scale application of floating solar farms as a critical strategy for ensuring Nigeria's sustainable and reliable electricity supply.

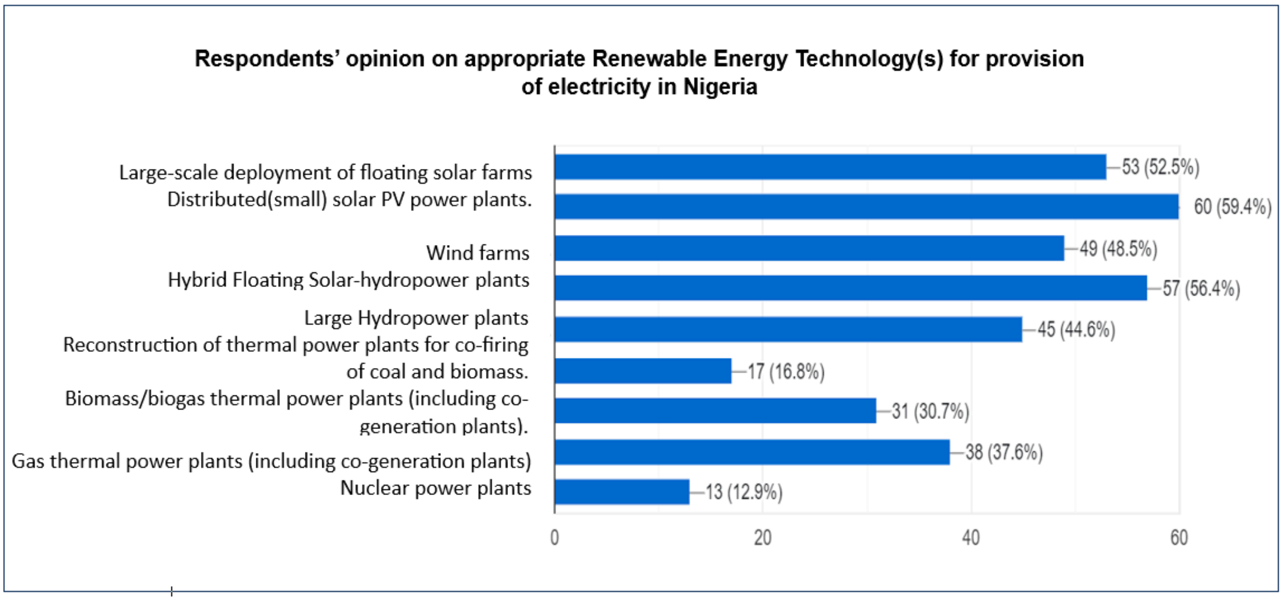
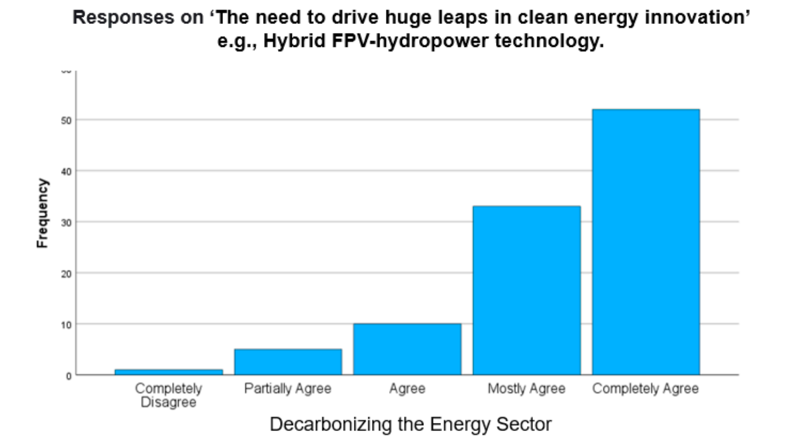


Figure 5. Preferred renewable energy technologies for electrification in Nigeria, according to the respondents.

Furthermore, the survey probed the participants on potential strategies for decarbonizing Nigeria's energy sector by 2050. In Figure 6, an overwhelming 85% of respondents agreed that significant strides in clean energy innovation, particularly in technologies like floating solar or hybrid renewable energy systems, are essential for decarbonization. Only a tiny fraction, between 1% and 5%, disagreed or somewhat agreed with this perspective, demonstrating that one way to decarbonize the energy sector would require considerable leaps in clean energy innovation. Additionally, 94% of the participants underscored the importance of incorporating bioenergy and carbon capture, utilization, and storage (BECCUS) technologies as pivotal to the decarbonization process, highlighting the role of these existing yet not vastly deployed tools beside emerging innovative technologies in achieving a sustainable energy future.



	N	%
Completely Disagree	1	1.0%
Partially Agree	5	5.0%
Agree	10	9.9%
Mostly Agree	33	32.7%
Completely Agree	52	51.5%

Mean	4.29
Std. Deviation	0.909

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	24.321[a]	16	0.083
Likelihood Ratio	23.231	16	0.108
N of Valid Cases	101		

a. 16 cells (64.0%) have expected count less than 5. The minimum expected count is 0.10

Figure 6. Respondents' opinion on 'The need to drive huge leaps in clean energy innovation'.

Some Case Studies of FPV-HEPP Applications

Several studies have been conducted on co-locating solar PV with hydropower, and the following examples showcase its potential and where it has been deployed. This technology has been deployed in sub-Saharan Africa and regions with similar geographical, socio-economic, and political settings or statuses. One example of this is the 50-megawatt (MW) phase of the 250 MW solar—hydro hybrid project by the Bui Power Authority (BPA) in Ghana, where it doubled the country's grid-connected solar energy and reduced greenhouse gas emissions by over 47,000 tons per year. Similarly, a study and simulation on the High Dam and Aswan Reservoirs in Egypt after hybridizing with floating solar PV indicate that additional energy of up to 11.9 GWh/year and 11.3 GWh/year, respectively, can be generated, with an estimated water saving of up to 0.1 million cubic meters from both dams. The study also shows that installing single-axis tracking-type FPV results in higher energy generation of 4.96%, with the proposed hybrid FPV–hydropower plant also able to contribute to limiting emissions of up to 44,270.6 tons of CO_2.

Another example is the 192 MWp floating solar plant in Indonesia, which is operational and expected to produce approximately 300 GWh/year, powering 50,000 homes, [32] and reducing carbon dioxide emissions by 214,000 tons. This showcases the scalability of solar PV with hydropower, a key aspect of its potential. Malaysia's national energy transition plan (NETR) includes developing the Tenaga Nasional Berhad (TNB) hydro dam lake, following the success of its floating solar trial project at the Sultan Azlan Shah Power Station (SJSAS) in Perak. The floating solar PV project generated over 600 MWh of energy, reduced CO_2 emissions by 390 tons over four years of operation and is anticipated to generate roughly 2500 MW of electricity, a testament to the power of this technology. Analysis of solar photovoltaic energy potential in Brazilian hydroelectric reservoirs through floating panels [32] was calculated, using 10% of the area of the country's four largest hydroelectric power plants, they generated 47,910 GWh of energy annually, which is a remarkable achievement. The results from a simulation of FPV at the Gaviao reservoir in NE Brazil also indicate that 81% coverage of the reservoir areas by FPV generates 835,820 MWh of electricity. This amount is estimated to meet 19% of Fortaleza city's energy demand, with a population of 2.6 million people, which is a significant contribution to the city's energy needs.

India is another country that has embraced and deployed this technology. GIS-based studies on potential assessment of floating photovoltaic systems in reservoirs of Tamil

Nadu [33] estimated that India's available surface area for FPVs is 18,000 km² with a potential capacity of 280 GW. The Sobradinho and Tucuruí plants were estimated to have FPV potentials of 112,632 GWh/year and 59,906 GWh/year, respectively, four and two times the plant's annual electricity generation. The potential energy generation of the Itaipu plant in its reservoir is about 29 TWh/year but does not exceed the actual hydroelectric generation levels of the plant. Furthermore, a study of the potential of installing FPV in 117 hydroelectric reservoirs in India [34] under different scenarios putting into consideration pontoon-type floating structures shows that with a conservative coverage of 4% of these reservoirs by FPV, the energy generated from these hydroelectric power plants (HEPPs) can double their installed capacity and increase their electricity output by 52%, generating an additional 66.56 TWh annually and a total of 837 million m^3 per year of water being saved, resulting in an additional annual hydroelectricity of 1.566 TWh.

In China, the state-owned renewable energy developer, China Energy Conservation and Environment Protection Group (CECEP), partnered with Ciel and Terre Company of France to create a 70 MW floating solar project in Suzhou City's Yongqiao District in Anhui Province. The project uses monocrystalline PV modules manufactured in China and spans across 13 separate islets on 140 hectares, completed in 2018. An individual 18 km long 110 V overhead line was built for the grid connection of the plant. The floating solar plant can generate over 70,000 MWh of electricity annually, equivalent to powering almost 21,000 households. At the time of completion, the project was one of the largest of its kind. The World Bank has reported the benefits of electricity generation from solar PV panels mounted on floating platforms, including low opportunity costs, reduced evaporation, and comparatively low construction, installation, and maintenance costs. This technology, with its economic advantages, is applied in both developed and developing countries, and is particularly suitable for locations where land is relatively scarce and expensive. Around 70 larger-scale floating PV projects are operational or under construction, and their number is increasing rapidly. Singapore boasts an impressive and massive floating solar farm on the Tengeh Reservoir. It covers an area equivalent to 45 football fields and has 122,000 floating solar panels. This facility plays a crucial role in powering Singapore's five water treatment plants and aligns with the country's ambitious goal to quadruple solar energy production by 2025, a testament to the financial viability of this technology.

5. Hybrid Floating Solar PV–Hydropower Systems: Advantages, Implementation Challenges, and Deployment Barriers in Sub-Saharan Africa

5.1. Advantages of Integrating Floating Solar Panels with Hydropower Systems

Integrating floating solar photovoltaics with hydropower systems, known as hybrid FPV–hydropower systems, offers a suite of benefits. These systems not only conserve resources by mitigating water evaporation through reduced airflow and solar irradiance, thereby augmenting water availability for hydropower generation, but they also enhance operational flexibility [20,35]. The potential of this technology is particularly evident in its ability to provide a higher degree of generation control and compensate for the intermittent nature of solar PV output. Additionally, the spatial efficiency of FPVs is highlighted by their minimal land footprint [36,37] since the panels are mounted atop existing dam structures, thus alleviating land use conflicts. The underlying water bodies also cool the PV panels, enhancing their operational efficiency [21,38].

Moreover, the shade cast by the panels aids in reducing algal growth and water loss due to evaporation, which, in turn, improves hydroelectric output and water quality [34,36]. The hybrid model opens avenues for energy storage solutions, from utilizing surplus solar energy in pumped storage schemes to optimizing water conservation during peak solar production periods. The co-location of FPVs with hydropower facilities facilitates seamless integration with existing grid infrastructure, translating to cost savings in transmission connectivity [38]. Such integration also enhances the utilization efficiency of transmission lines by tapping into any surplus transfer capacities. The aquatic setting of FPVs offers an unobstructed solar capture environment, further amplified by the reflective properties of water surfaces, thus optimizing solar energy harvest. The strategic placement of solar arrays atop dams serves as a protective barrier against direct solar exposure, potentially extending the lifespan of these critical infrastructures by mitigating thermal stresses [39]. The inclined mounting of solar panels optimizes space utilization, effectively reducing the inter-panel spacing required compared to conventional flat-terrain installations, thereby maximizing solar energy capture.

5.2. Challenges in Implementing FPV–Hydropower Systems

Despite the promising benefits, floating solar PV systems face several deployment challenges. These include the novelty of this approach, which raises questions about the long-term viability and environmental impacts, coupled with uncertainties surrounding cost-effectiveness and the technical intricacies associated with aquatic installations, particularly anchoring, mooring, electrical safety, and maintenance. These systems must be engineered to withstand significant wind forces, necessitating robust mooring solutions. Additional concerns include potential interference with recreational water use, aesthetic considerations, and environmental ramifications such as temperature fluctuations that may disrupt local ecosystems. Prolonged exposure to humidity could accelerate the wear and tear of PV modules. At the same time, floating structure corrosion and debris accumulation pose risks to both the local environment and the hydropower infrastructure. Also, variability in the cost of electrical, anchoring, and mooring systems is often higher than their terrestrial counterparts, and the possibility of operational disruptions due to insulation failures presents further hurdles. The operational dynamics of FPV–hydropower hybrids might be constrained by the inherent ramping capabilities of hydro turbines, which may need help to match the pace of fluctuations in solar output.

5.3. Barriers to Hybrid Floating Solar PV–Hydropower Technology Deployment in Sub-Saharan Africa

While the rollout of FPV technology does indeed face numerous obstacles across economic, environmental, technical, regulatory, and cultural domains, it is important to note the significant potential benefits. Technical barriers, for instance, encompass operational and engineering challenges that could hinder the seamless integration of FPVs, including transmission and interconnection limitations that may strand FPV assets due to inadequate infrastructure planning [40]. The deployment of FPVs could be further complicated by the unpredictability of extreme weather phenomena and their impacts, alongside uncertainties regarding the durability, reliability, and environmental compatibility of FPV installations [24]. Non-technical barriers span regulatory, institutional, economic, and socio-cultural factors that inhibit technology adoption, such as the absence of incentives for novel renewable technologies and public apprehensions regarding the visual and functional implications of FPVs on water bodies. Environmental concerns primarily revolve around the potential ecological impacts of FPVs, with uncertainties surrounding their effect on aquatic ecosystems [41] potentially hindering deployment due to heightened public scrutiny and extended environmental review processes. Regulatory challenges, such as ambiguities in water rights and legal frameworks, can delay FPV projects, with the regulatory landscape often complicating the permitting and approval processes for FPV installations on both artificial and natural water bodies. Cultural resistance, stemming from a lack of public acceptance or negative perceptions based on past experiences with renewable projects, can pose significant barriers to the widespread adoption of FPV technologies. Economic obstacles, including policy inconsistencies and subsidies favoring fossil fuels, can skew the competitive landscape against emerging technologies like FPVs, deterring private investment and hindering the broader adoption of renewable energy solutions.

Table 3 provides a comprehensive overview of the barriers and potential of floating solar PV (FPV) systems, specifically tailored to the context of sub-Saharan Africa. The analysis draws on a range of studies, offering insights into the unique challenges and opportunities that this region faces. Technical barriers, such as immature supply chains and grid integration complexities, are juxtaposed with the potential benefits of higher energy yield and suitability for land-scarce areas. Economic challenges, including high initial costs and financing difficulties, are balanced against long-term economic benefits and infrastructure utilization. Environmental concerns are weighed against benefits like water conservation and reduced land use impact. Cultural and policy barriers are also considered, along with the potential for increased energy security and alignment with climate change mitigation efforts.

Table 3. Barriers and potential of FPV systems in sub-Saharan Africa.

Barrier Type	Example Barriers	FPV System Potential	References
Technical	- Immature technology supply chains - Grid integration complexities	- Higher energy yield due to cooling effects - Suitable for areas with limited land availability	[20,25,35]
Economic	- High initial investment costs - Financing difficulties - Shortage of a trained workforce and training institutes to build a trained FPV workforce	- Long-term cost-effectiveness - Utilization of existing hydropower infrastructure	[24,25,37]
Environmental	- Potential impacts on local aquatic ecosystems	- Water conservation through reduced evaporation - Minimized land use impact	[29,35,41]
Cultural & Policy	- Public acceptance challenges - Lack of supportive policies - Lack of cooperation & appropriate coordination amongst regulatory agencies	- Increased energy security - Alignment with climate change mitigation goals	[10,13,40]

(Source: Author).

6. SWOT Analysis of Hybrid Floating PV–Hydropower Systems

SWOT is an acronym for Strengths, Weaknesses, Opportunities, and Threats. A SWOT analysis is a strategic planning and management technique and framework used to help a person, organization, or business entity identify, assess, and understand the internal and external forces that may create opportunities or risks. It is a valuable tool for evaluating the current and future potential of organizations, projects, or business ventures. A SWOT analysis helps in the decision-making process and aids in forecasting/predicting the success of the project. The strengths, weaknesses, opportunities, and threats of floating photovoltaic plants are highlighted in the following section.

6.1. Strengths

These are the characteristics that give the business a competitive advantage over others. The following are identified strengths of FPV–hydropower systems:

- Increased energy generation: Hybridizing floating PV with hydropower reservoirs or water bodies results in more energy generation due to the cooling effect of water.
- Increased efficiency: Natural cooling light reflected from water and evaporating water keeps the solar panel's temperature below ground temperature, which increases efficiency compared to ground-mounted PV systems.
- Resource conservation: Installing FPV on hydropower reservoirs can lead to resource conservation, as it may help reduce water evaporation through decreased airflow and absorption of solar radiance, increasing resources for hydropower generation.
- Reduced algal growth: The shading provided by PV panels on the water reduces algae growth and evaporation, thus improving hydro-energy generation and water quality.
- Cost-effective energy generation: Co-locating FPV with hydropower allows connection to existing transmission infrastructure, thus reducing transmission interconnection costs.
- Reduced water evaporation: The floating systems on which the solar photovoltaic panels are installed provide a shadow on the water surface, which reduces water losses due to evaporation.

- Improves water quality: Photosynthesis and algae growth decrease, improving water quality.
- Generates less dust: Areas with high solar potential are generally dusty and dry. Thus, the floating photovoltaic systems operate in a less dusty environment than their counterparts on the ground.
- Efficient land use/land conservation: Convert unused non-commercial water into profitable solar PV power plants to save valuable land for local agriculture, mining, tourism, and other incentives.
- The floating platforms are 100% recyclable, which can withstand ultraviolet rays and resist corrosion.
- The ease of grid connectivity improves system reliability.
- It minimizes land requirements and, thus, conflicts arising from ownership.
- New transmission lines are not needed as power plants are close to infrastructure, thus reducing transmission costs).

6.2. Weaknesses

Weakness indicates the characteristics that disadvantage the business or organization relative to its competitors. The identified weaknesses include the following:

- Vulnerability to weather conditions: Risk of damage to the solar panels with time due to potential saltwater and wake effects (though location dependent).
- As a nascent and relatively immature technology, the durability of FPV systems has yet to be fully confirmed.
- More knowledge and experience are needed about the technology than mature and conventional ground-mounted PV systems.
- Long-term maintenance requirements: Fouling floating structures and debris accumulated on a river or lakeshore must be cleaned regularly.
- Limited guidelines and regulations.

6.3. Opportunities

These elements in the external environment allow it to formulate and implement growth strategies. FPV–hydropower systems could provide the following potential opportunities:

- FPV–hydropower systems could provide energy storage opportunities through different configurations, e.g., coupling FPV with pumped storage hydropower to use excess solar energy to pump water into an upper reservoir and store it for future use.
- Potential for international market growth. This provides potential investment opportunities and markets in developing and emerging economies, as well as global market growth.
- This technology is a promising solution to address energy access barriers in developing countries endowed with significant solar irradiance and water bodies.
- Expansion in untapped water bodies.

6.4. Threats

The threat involves elements in the external environment that can endanger the business and its ability to operate. The following could pose a danger to FPV–hydropower systems:

- Environmental concerns: The system is threatened by numerous threats, such as tides, storms, ocean waves, cyclones, and tsunamis.
- Moisture and temperature changes in the panel may cause negative temperature values, reducing total electrical efficiency.
- There are concerns regarding durability under humid and corrosive weather conditions.
- Concerns about intrusion on recreational water bodies, aesthetics, and environmental impacts, such as temperature fluctuations, could negatively impact the nearby ecosystems.
- Depending on the location, fishing and other transportation activities may be disrupted.

- Metal structures are prone to deterioration from harsh weather conditions that can reduce the system's lifespan. This reduces the infiltration of sunlight into the water and prevents animals, algae, etc., from living in it.
- Threats from competing technologies: The prevalence and widespread acceptance of similar energy generation technologies, such as ground-mounted PV systems and wind energy, are more mature technologies that have gained much popularity and public acceptance.

7. Limitations of This Study

This study takes a unique approach by focusing on the potential role of innovative technologies in sub-Saharan Africa, explicitly floating solar farms. It explores the benefits of hybridizing floating PV with existing hydropower plants. It delves into how these innovative solutions can aid the transition from fossil fuel-based energy to a clean or low-carbon energy system in the region. The practical implications of these findings are also underscored. The geographical location is limited to Nigeria and sub-Saharan Africa. The participants surveyed are limited to Nigeria. While data analysis from an ongoing study is still in progress, only a limited number of responses from the participants have been presented from the ongoing survey. While this study has stated that reducing carbon dioxide or GHG emissions is one of the advantages of deploying low-carbon innovation technologies such as FPV-HEPP systems, it does not intend to experiment on this. However, the authors' ongoing studies on the technical potential of floating solar PV in Nigeria are committed to presenting experimental results on how FPV can reduce carbon emissions.

8. Conclusions

The transition from a predominantly fossil fuel-based energy system to a low-carbon energy system in sub-Saharan Africa is both an economic imperative and a societal challenge. Our study surveyed 101 regional stakeholders and underscored the urgent need for a comprehensive and forward-thinking policy framework that spans the entire technological lifecycle—from initial prototypes to widespread commercialization. These findings highlight the pivotal role of government support in fostering the decarbonization process, emphasizing the importance of long-term strategies that are supported by detailed clean energy plans tailored to the specific needs of local infrastructure and technology.

The insights garnered from our survey respondents reveal a consensus on the critical role of innovation in utilizing existing technologies to reduce greenhouse gas emissions significantly. Achieving this requires enhanced knowledge exchange and collaboration across various sectors and geographical regions, underscoring the importance of a collective effort in driving the energy transition forward and making each stakeholder feel a sense of shared responsibility and involvement. Innovation should extend beyond research, development, and demonstration, encompassing the foundational technologies and infrastructure that underpin these solutions, such as integrated grids and battery storage.

The SWOT analysis presented in this study, together with output efficiencies and case studies of floating solar PV when co-located with hydropower plants, its application in sub-Saharan Africa, and other regions with similar geographical features, could serve as a valuable tool for stakeholders to make informed decisions regarding the deployment of this technology.

The potential of large-scale deployment of floating solar technology on hydropower reservoirs in Sub-Saharan Africa, as highlighted by our respondents, offers a promising solution to offset hydropower variability, conserve water, and meet the growing energy demands of the continent's growing population, thereby enhancing resilience to climate change without the need for extensive infrastructural modifications.

As indicated by our survey, a dedicated effort is required to address the multifaceted barriers identified to fully realize the potential of floating photovoltaic (FPV) systems in Sub-Saharan Africa. These include technical, economic, environmental, cultural, and regulatory challenges that impede the widespread adoption of FPV technology. By tackling these barriers head-on, sub-Saharan Africa can harness the full benefits of FPV systems, contributing significantly to the global endeavor towards sustainability and environmental conservation.

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