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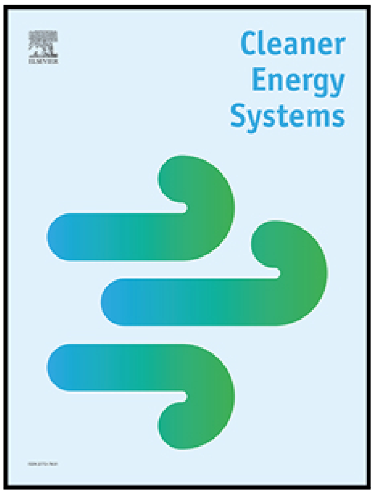

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Highlights

- Northern Nigeria has untapped renewable resources: 210 GW solar PV, 88.7 GW CSP.
- Policy inconsistency hinders renewable policies like NREEEP and NESP.
- Grid upgrades and local expertise are crucial for renewable energy integration.
- Global trends and lower tech costs boost renewable energy investment in Nigeria.
- Strategies for solar PV in Northern Nigeria: awareness, mini-grids, training.

A SWOT Analysis approach for the development of Photovoltaic (PV) energy in Northern Nigeria

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Abstract

This research employs a comprehensive Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis to investigate the advancement of photovoltaic (PV) energy in Northern Nigeria. The study delves into the intricacies of introducing PV systems within the context of economic challenges, including issues such as currency volatility and inflation, which amplify costs and impede capital investments. Environmental factors, such as dust and sandstorms, are identified as obstacles diminishing the efficiency of solar panels. Additionally, security concerns in remote areas elevate operational costs and influence investment decisions. This paper proposes effective mitigation strategies, encompassing widespread public awareness campaigns to augment market engagement, the establishment of mini-grid systems for enhanced energy distribution, customised on-the-job training programs to foster local expertise in PV technology, and the utilisation of micro-grid systems as experimental grounds for regulatory and policy testing. By synthesising these components, the study offers a comprehensive overview of the prerequisites essential for the successful proliferation of PV energy in Northern Nigeria. Emphasis is placed on the potential for solar energy to significantly contribute to the region's sustainable development and achieve energy independence when the identified strength, and opportunities are exploited. The key strength identified are the average Global horizontal irradiance (GHI) of 5.436kWh/m^2, Direct Normal Irradiance (DNI) of 1534-1680kWh/m^2, Levelised Cost of Electricity (LCoE) of $ 0.1, and an opportunity to fully utilise the over $ 7.88 million grant authorised by the African Development Bank (AfDB) from the Sustainable Energy Fund for Africa.

Keywords: Solar Photovoltaics, SWOT Analysis, Renewable Energy, Sustainable energy, Clean Energy.

1 Introduction

1.1 Motivation

As the global community grapples with the urgent need for sustainable development and climate action, the role of renewable energy sources has never been more critical. While countries around the world are making strides in shifting away from fossil fuels, the challenge is particularly acute in developing nations where energy demand is growing rapidly alongside economic development. One such country is Nigeria, Africa’s most populous nation and largest economy, where energy demand is set to soar in the coming decades. Access to reliable, sustainable energy is not just a matter of convenience; it is a prerequisite for achieving socio-economic objectives such as poverty alleviation, healthcare improvement, and industrialisation (Bhatia and Angelou, 2015).

Despite being rich in oil and gas reserves, Nigeria faces an acute energy crisis. Surprisingly, only about 65.9% of the population has access to electricity, and where it does exist, it is often unreliable (IEA, 2019). This stark reality severely hampers economic growth and perpetuates inequality, making the search for alternative, reliable energy sources a national imperative. Northern Nigeria, in particular, is blessed with abundant solar resources, receiving an average of 6.5 hours of sunlight per day (Eltawil & Zhao, 2010). This natural advantage offers a promising avenue for solar energy deployment, yet the region remains underserved and underdeveloped in terms of its solar energy potential. The urgency to explore and harness cleaner forms of energy is further motivated by Nigeria's commitment to global climate goals, including its pledge to reduce greenhouse gas emissions unconditionally by 20% by 2030 under the Paris Agreement (Oka, 2019). The development of Photovoltaic (PV) energy in Northern Nigeria not only aligns with global sustainability goals but also has the potential to alleviate regional energy poverty, foster economic growth, and reduce carbon emissions.

1.2 State of the art

Nigeria's energy (electricity) generation has undergone various transitions from one technology to another. Historically, coal-fired steam turbines and hydroelectric plants were the primary sources of electricity until the late 1970s, when natural gas-fuelled turbines were introduced which now accounts for about 86% of the country’s energy generation (Edomah, 2021). Currently, a total of twenty-three grid-connected power plants comprising twenty gas-fired and three hydroelectric power plants with a combined installed capacity of 12,522 MW makeup Nigeria's energy supply system (Ibrahim and Ayomah, 2022). The overall installed capacity of the available generating units as of 2018 was 8,792MW (Ogunrinde et al., 2019). The transmission corporation, which manages the nation's electrical transmission network has a capacity of 7500 MW (Saturday, 2021).

In addition to the gap between the generation and transmission capacities, the deficit of electricity supply in Nigeria relative to its aggregate demand has been attributed to several factors such as; gas price fluctuations, availability and other socio-political elements, inefficient and outdated generation, transmission, and distribution networks (Udeani, Jaramillo and Williams (2021), inconsistent energy policies, shortage of skilled manpower, theft and vandalism, and weather related issues such as drought and flooding. This energy deficit has driven the need for self-generation and consumption of electricity (Babajide and Brito, 2021). The most common method for self-generation has been the use of fossil fuel powered generators, which pose a health (Olusegun and Adeoye, 2017; Banzer et al., 2022) and environmental concern (Jacal et al., 2022; Emoyen, Agbaire and Ohwo, 2022).

The abundance of clean, inexhaustible, and renewable solar resources in Nigeria particularly in the northern part of the country offers a cleaner and sustainable solution in meeting residential and commercial electricity demands. With the introduction of feed-in tariff (FIT) programmes and various government subsidies in many regions of the world, the solar power industry's technology is constantly evolving and improving with a recorded 200-fold increase in 17 years as reported by Wall (2021) at the COP26 conference. This growth of solar PV panel technology has resulted in a steady decline in the price of PV modules, making solar PV more attractive and acceptable. There is an abundance of literature on solar off-grid applications particularly in rural and remote settings as well as a variety of material on urban settings in developed countries.

1.3 Contribution of the work

The core contribution of this study lies in its targeted, in-depth exploration of the Photovoltaic (PV) energy landscape in Northern Nigeria through the lens of a comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. The subject of renewable energy has been extensively studied in diverse global contexts, but this work seeks to fill a significant gap in the existing literature by focusing on the unique conditions and untapped potential of Northern Nigeria—a region characterised by abundant solar resources yet constrained by a multitude of challenges. By employing a SWOT framework, this study goes beyond mere descriptive analysis to provide actionable insights that are critical for policymakers, investors, and local communities. The methodology allows for a detailed understanding of the sector by not only identifying the strong suits and limitations of existing infrastructure but also by pointing out the windows of opportunity and potential risks associated with the development of PV energy in this region. The paper expands the discourse by dissecting various dimensions affecting the PV sector—technical, economic, environmental, and socio-economic. By adopting this multi-faceted approach, the study offers a more holistic view that captures the complexities and interdependencies of these dimensions. In terms of theoretical implications, this study contributes to the broader academic dialogue surrounding renewable energy in developing countries. It argues for a more localised, region-specific approach to energy policy and planning, providing empirical evidence that could be beneficial for similar studies in other developing nations with abundant yet underutilised renewable resources.

1.4 Structure of the paper

The rest of the paper is organised into the following: Section 2 present a background and review on renewable energy in Nigeria. In section 3, the strengths, weaknesses, opportunities, and threats of Photovoltaic in northern Nigeria are investigated. Section 4 presents key strategic plans on the way forward and key performance indicators to measure progress. Section 5 provides the conclusions and discuss further research areas as well as the limitations of the current work.

2 Background

2.1 Solar Off-grid Applications in Rural and Urban Settlements

The topic of solar off-grid applications, particularly in rural and remote settings, has garnered significant attention in the literature, with numerous studies exploring its potential and challenges. Additionally, there is a wealth of material on solar applications in urban settings, particularly in developed countries, highlighting various implementation strategies and outcomes (Book and Sayigh, 2024; Adewumi et al., 2024). This literature review provides an overview of key findings and trends in both rural and urban contexts, drawing from a range of scholarly sources.

In rural and remote settings, solar off-grid applications have emerged as a promising solution to address energy poverty and improve livelihoods. Researchers such as Kulkarni and Anil (2014) have emphasised the socio-economic benefits of solar off-grid systems, including enhanced access to electricity, income generation opportunities, and improved healthcare and education outcomes. Moreover, study by Bose et al. (2021) have highlighted the role of solar microgrids and decentralized energy systems in promoting energy access and sustainability in remote areas.

Furthermore, the literature underscores the importance of addressing technological, financial, and institutional barriers to the widespread adoption of solar off-grid solutions in rural contexts. For instance, research by de Almeida et al. (2020) has identified key challenges such as high upfront costs, limited access to finance, and inadequate policy support, which hinder the scalability and sustainability of off-grid solar initiatives in rural areas.

In contrast, studies focusing on urban settings in developed countries have explored the integration of solar energy into existing infrastructure and urban planning frameworks. Research by Wang et al. (2023) and Elhabodi et al. (2023) have examined the role of solar photovoltaics (PV) in mitigating urban heat island effects, reducing greenhouse gas emissions, and enhancing energy resilience in cities. Additionally, authors such as O'Dwyer et al. (2019) and Akrofi & Okitasari (2022) have highlighted the potential of solar-powered buildings and smart grid technologies to transform urban energy systems and promote sustainable urban development.

Moreover, the literature emphasises the importance of policy support, public-private partnerships, and community engagement in driving the adoption of solar energy solutions in urban contexts. For example, study by Batidzirai et al. (2021) have underscored the need for supportive regulatory frameworks, incentives, and public awareness campaigns to accelerate the deployment of solar technologies in urban areas. The insights from both rural and urban applications of solar off-grid solutions underline the universal relevance of renewable energy strategies, setting the stage for a deeper dive into specific national contexts like Nigeria. Here, the interplay of abundant natural resources, energy challenges, and the evolving role of renewables presents a unique context to explore sustainable energy solutions tailored to diverse local needs and conditions.

2.2 Renewable Energy in Nigeria

Nigeria, one of the most populous countries in Africa, boasts of abundant natural resources, including substantial reserves of fossil fuels like oil and gas. Despite these endowments, the nation grapples with a persistent energy crisis that affects both urban and rural populations. To address this deficit and transition to sustainable practices, attention has increasingly turned towards renewable energy sources. These sources are not only environmentally friendly but also abundant in the country, particularly in the Northern regions. The narrative surrounding renewable energy in Nigeria is complex, involving factors such as policy frameworks, socio-economic conditions, and technological advancements.

Nigeria is endowed with a plethora of renewable energy resources that remain largely untapped. The country's geographical location affords it significant solar, wind, hydro, and biomass resources (Ohunakin et al., 2014). Solar energy, for instance, has been reported to be abundant especially in Northern Nigeria, where average solar radiation is about 6.5 hours per day (Eltawil & Zhao, 2010). Similarly, wind energy potential has been assessed at different parts of the country, with the coastal and northern regions showing promise for significant wind power development (Okeniyi et al., 2015). However, the harnessing of these resources has been disproportionately low. According to the International Renewable Energy Agency (IRENA), Africa has about 50% of the world's renewable energy potential, but its current contribution to global renewable energy is less than 10% (IRENA, 2020). This underscores a glaring paradox: while the resources are abundant, their conversion into usable forms of energy has been minimal. This unexploited potential represents both a significant opportunity and a substantial challenge for the country's energy future. It is important to note that the primary barriers are not just technological but also include factors such as policy inconsistency.

The Nigerian government has made a series of policy efforts to stimulate the adoption of renewable energy technologies across the country. Notable among these initiatives are the National Renewable Energy and Energy Efficiency Policy (NREEEP) and the Nigerian Energy Support Programme (NESP) (Nebo and Wakil, 2015). These policy frameworks are aimed at various objectives, such as improving the investment climate for renewables, fostering the development of mini-grids, and encouraging decentralised renewable energy solutions. The overarching goal is to diversify the energy mix and reduce the country's reliance on fossil fuels (Olatunji et al., 2018). NREEEP, specifically, has provisions that aim to make the investment climate more favourable for renewable energy projects. It seeks to provide tax incentives, reduced custom duties, and other financial mechanisms that would attract both domestic and international investors (Ozoegwu and Akpan, 2021). However, the extent to which these provisions have been effectively implemented is a subject of debate. The Nigerian Energy Support Programme (NESP), funded by the European Union and the German Government, focuses on decentralised renewable energy solutions. NESP provides technical assistance and capacity-building activities aimed at stimulating investments in renewable energy. One of its key objectives is to foster the development of mini-grids to serve off-grid communities, thus contributing to rural electrification (Isah, 2019). While the policies may appear comprehensive on paper, their implementation has faced multiple hurdles. According to a study by (Gungah, 2019), the impact of these policies has been relatively modest due to various factors such as implementation bottlenecks, policy inconsistency, and inadequate funding. Lilliestam and Patt (2015) further elaborate that the lack of continuity in government policies and bureaucratic red tape contribute to the sluggish pace of policy impact.

While various policies may look comprehensive and well-intentioned, there exists a disconnect when it comes to the technological and infrastructural readiness to support these policies. One of the most cited shortcomings is the existing electrical grid infrastructure, which is not optimally designed for the integration of large-scale renewable energy projects (Dada, 2015; Ugwoke, 2020; Medina et al., 2022). Unlike conventional energy sources, renewable energy often requires smart grids capable of handling the variability and intermittency associated with sources like solar and wind (Mlilo, Brown and Ahfock, 2021). Unfortunately, the existing infrastructure in Nigeria is not equipped to manage these unique challenges. The lack of technological and infrastructural readiness goes beyond immediate implementation challenges; it also has a stifling effect on potential investment. Investors usually assess the readiness of a country's infrastructure before committing resources to large-scale projects. The inadequate grid system, coupled with a lack of dedicated renewable energy facilities like wind farms or solar parks, tends to discourage potential investors (Iwayemi, 2008). This leads to a cyclical problem where the lack of investment results in stagnant technological and infrastructural development, which in turn further discourages investment (Anyanwu, 2006). Beyond grid infrastructure, other technological elements necessary for the effective deployment of renewable energy are lacking. For example, there is limited local expertise in the installation and maintenance of renewable energy systems (Yakub et al., 2022). Moreover, local manufacturing capacity for renewable energy components such as solar panels or wind turbines is virtually non-existent, making the country dependent on imports and thereby increasing the cost of renewable energy projects (Charles and Majid, 2023). The future of renewable energy in Nigeria appears optimistic due to a combination of local and global factors. On a global scale, there is an increasing emphasis on sustainable energy solutions, largely driven by climate change concerns and international accords such as the Paris Agreement (Iacobuţă, 2022). As Nigeria is a signatory to these global initiatives, the country faces growing external pressure to decarbonise its energy sector. This translates into a more conducive policy environment for renewable energy, making it likely that supportive policies will not just be formulated but may also see more robust implementation. Additionally, the trajectory for renewable energy in Nigeria is further strengthened by technological advancements that have made renewable energy systems more efficient and cost-effective. According to Wimalaratna (2022), the cost of installing renewable energy systems like solar panels and wind turbines has significantly decreased over the last decade, making them more financially accessible. This is particularly relevant for Nigeria, where cost has often been a barrier to the adoption of new technologies. The falling costs open new opportunities for both urban and rural electrification using renewables thus enabling larger scale deployment as can be seen in Figure 1.

Another encouraging development is the growing interest from the Nigerian diaspora and foreign investors in the renewable energy sector. Such engagement can bring in much-needed financial resources and technical expertise to a sector that has traditionally been underfunded and lacking in local expertise (Enayaba, 2023). The diaspora community, with its exposure to advancements in renewable energy in other parts of the world, can act as a bridge, bringing in not only investment but also new technologies and business models that have succeeded elsewhere. It is also worth noting that the increasing affordability and availability of renewable energy solutions can create a synergy with other sectors, such as agriculture and manufacturing, thus driving economic growth and job creation (Mutezo, G. and Mulopo, 2021). Renewable energy can help power irrigation systems, food processing plants, and small-scale factories, thereby contributing to a more sustainable and self-reliant economy (Majeed, 2023).

Figure 1: EEP solar hybrid power plant at Bayero University, Kano state (REA, 2019)

3 SWOT Analysis

SWOT analysis has long served as a cornerstone in strategic planning and decision-making processes (Leigh, 2009). In the context of solar energy development in northern Nigeria, this framework assesses the interplay of internal strengths and weaknesses alongside external opportunities and threats (see Figure 2).

Within Northern Nigeria, inherent strengths are evident, including expansive terrain and abundant solar irradiance. These attributes offer a solid foundation for solar energy development. Moreover, there are opportunities for growth, such as increasing awareness of climate change, decreasing costs of solar equipment, and burgeoning market demand.

However, certain weaknesses must be addressed to fully capitalise on these opportunities. Challenges related to regulatory and policy frameworks, as well as institutional capacity, need attention. Additionally, external threats like economic instability and security concerns pose significant obstacles. Addressing weaknesses while leveraging strengths and opportunities is essential for overcoming threats and advancing solar energy development in northern Nigeria. By doing so, the region can achieve significant milestones in sustainable energy deployment, contributing to both local prosperity and global environmental goals.

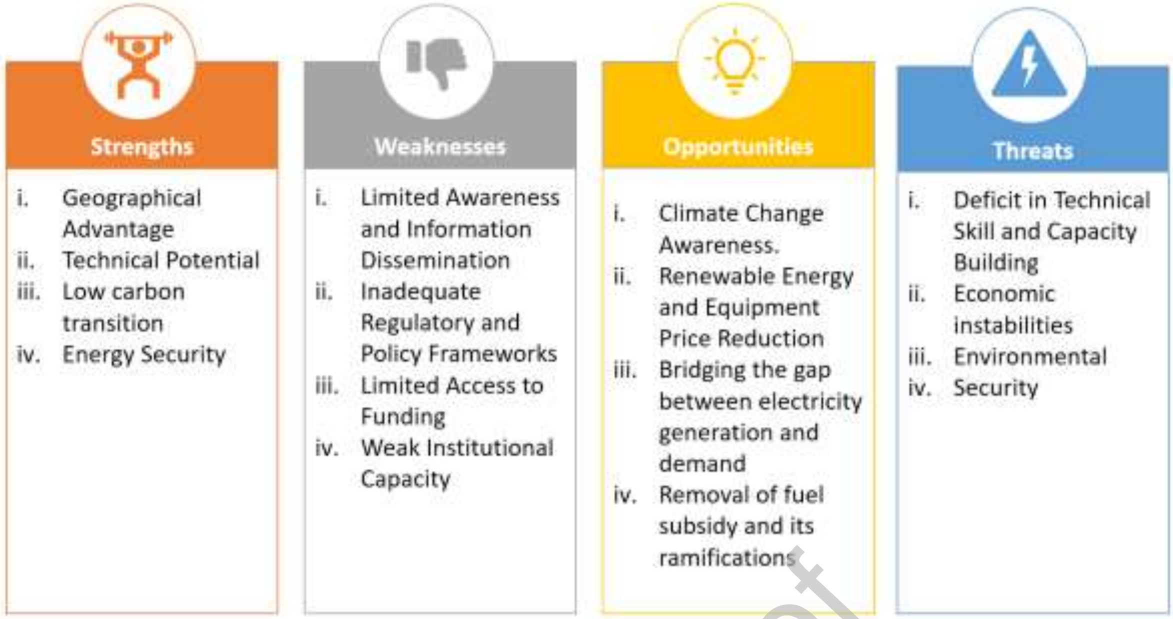

Figure 2: Summary of SWOT of PV Energy Development in Northern Nigeria

3.1 Strength

The strengths of northern Nigeria in terms of photovoltaic (PV) energy development are rooted in its natural resources, geographical location, and potential for economic growth. By leveraging these strengths, northern Nigeria can unlock its vast potential for solar PV energy development, contributing to sustainable economic growth, energy security, and environmental conservation.

3.1.1 Geographical Advantage

The key strength of northern part of Nigeria for producing electricity using solar resource is its geographical location characterised with abundance of solar energy (Bonah, 2020). Northern Nigeria is blessed with abundance solar energy resource with the highest values of average annual Global Horizontal Irradiation (GHI) from 2000 kWh/m^2 to greater than 2200 kWh/m2 as shown in Figure 3 and Direct Normal Irradiance (DNI) up to 1680 kWh/m^2 as in Figure 4 (The World Bank, 2020 and Lei et al., 2019).
The northern region of Nigeria and the country at large are blessed with vast natural sources of renewable energy resources such as solar that will be essential for sustainable development of the region. However, these resources are very much underexploited and underutilised (IRENA, 2023). The strength Solar resource in Northern region can be viewed using the following parameters: theoretical potential called Global horizontal irradiance, GHI (kWh/m^2), practical potential called Photovoltaic power output, PVOUT (kWh/kWp), Direct Normal Irradiance (DNI), Levelised Cost of Electricity (LCoE) as discussed subsequently.

3.1.2 Technical Potential

The technical potential for solar PV in Nigeria was estimated at 210 GW considering only 1% of the suitable land can be utilised for project development (IRENA and AfDB, 2022). The strength for Concentrated Solar Power (CSP) is also very significant with a potential of approximately 88.7 GW and mostly located in northern Nigeria (IRENA, 2023), where the DNI and PVOUT are highest as shown in Figure 4 and 5 respectively.

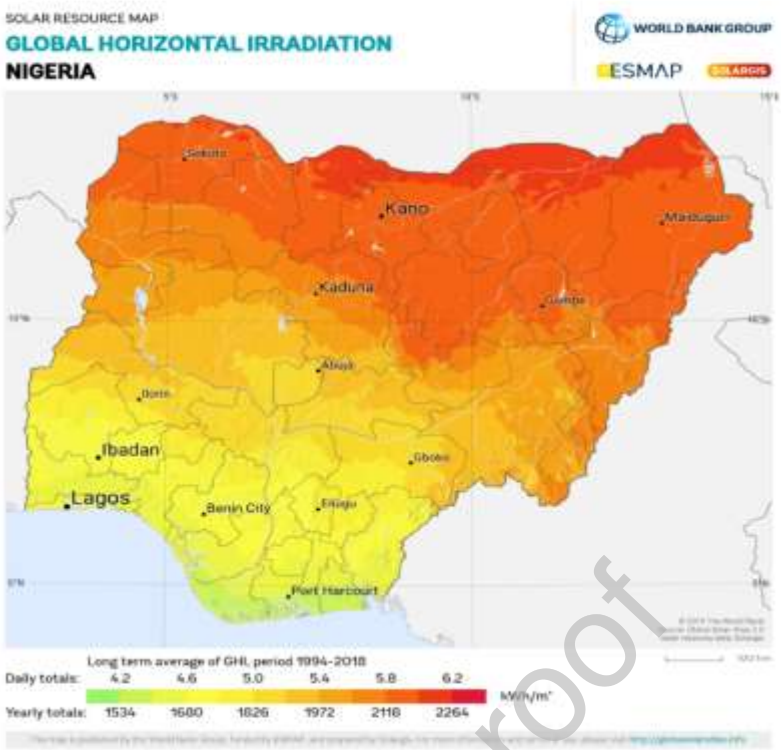

Figure 3: Average Daily and Annual GHI in Nigeria(Global Solar Atlas, 2024)

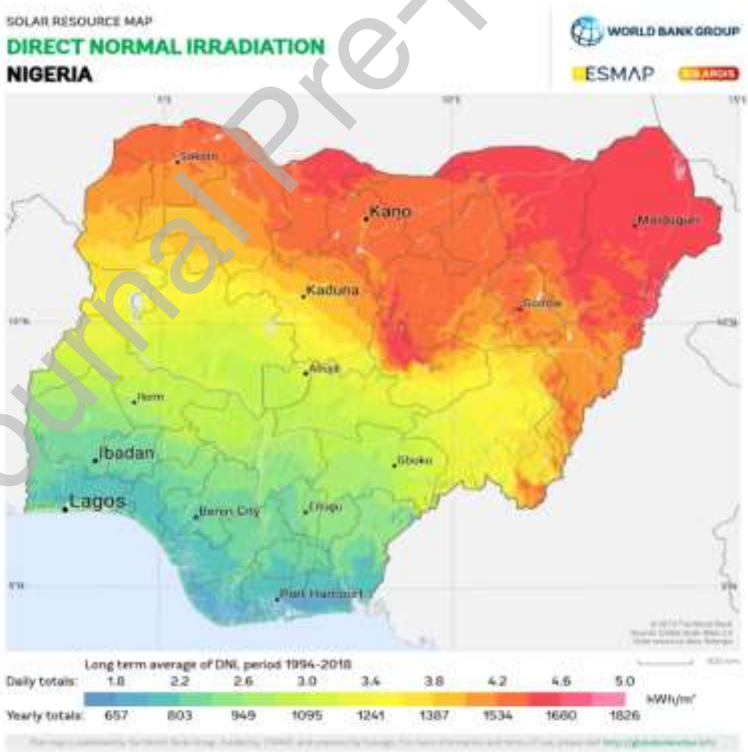

Figure 4: Average Daily and Annual DNI in Nigeria (Global Solar Atlas, 2024)

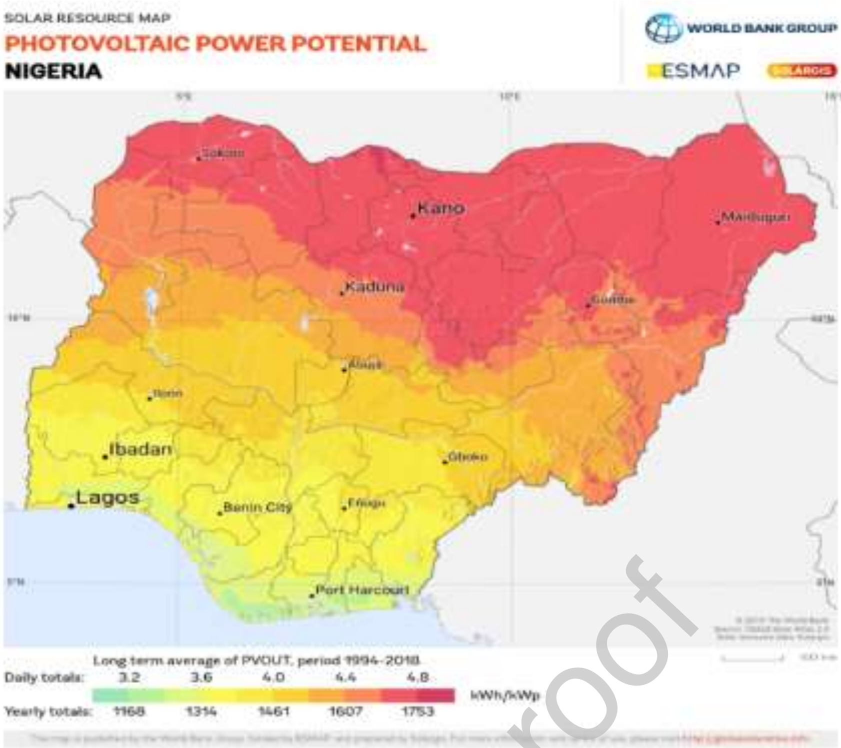

Figure 5: Average Daily and Annual PVOUT in Nigeria (Global Solar Atlas, 2024)

3.1.3 Low carbon transition

Solar radiation is essentially a free resource and ubiquitous across the globe. Transforming solar radiation into electricity is dominated by PV power plants, and in the current era of global climate change, PV technology becomes an opportunity to strengthen the countries and communities for transforming or developing their energy infrastructure and strengthen low-carbon energy transition in addition to lower LCoE of about USD 0.10 as shown in Table 1 (The World Bank, 2020 & Charles et al, 2020). The table below shows the summary of the strength indicators mentioned earlier and more.

Table 1: Summary of Solar PV Strength Indicators and Statistics in Nigeria

Indicator	Value
Average GHI/Rank	5.436 kWh/m^2/69
DNI	1534-1680 kWh/m2
PVOUT (Level 1/Rank)	4.298 kWh/kWp/102
LCoE	0.1 (0.09 – 0.12) USD
PV Installed Capacity (2018)	19 MWp
PV Equivalent Area	0.014%
Total Area/Equivalent Area	923,770/914,455 km^2
Electricity Consumption per Capita (2014)	145 kwh/annum

Considering the solar PV strength in the northern part of Nigeria discussed above, these could be summarised as derived from the geographical location, abundance of solar resource, and cost of energy (LCoE) production in the region.

3.1.4 Energy Security

Energy security in Northern Nigeria is significantly reinforced by its solar energy potential. The region's abundant sunlight provides a reliable and sustainable energy source that can greatly enhance energy independence and stability. By capitalising on the high Global Horizontal Irradiation (GHI) and Direct Normal Irradiance (DNI) values, Northern Nigeria can reduce reliance on imported fuels, mitigate energy supply disruptions, and contribute to a diversified energy portfolio. The shift towards solar energy not only supports a low-carbon transition but also promotes economic growth and infrastructure development. As solar technology becomes increasingly cost-effective, it presents a viable solution for long-term energy security, positioning Northern Nigeria as a leader in renewable energy within the region (Ugwoke et al., 2020).

3.2 Weakness

The shortcomings in the growth of photovoltaic (PV) energy in northern Nigeria are carefully studied in this section. Despite the region's vast solar potential, a number of obstacles prevent the efficient use and deployment of PV energy systems. This paper section identifies and discusses the main shortcomings in the development of PV energy in northern Nigeria through a thorough examination of the body of available material. The results help to clarify the obstacles and give policymakers, researchers, and practitioners new perspectives on how to deal with them and support the growth and development of sustainable solar energy in the area.

The development of PV energy systems is excellent in Northern Nigeria because of the area's plentiful solar radiation. However, several issues prevent the region's adoption of PV energy from moving forward. The goal of this analysis is to identify these flaws and suggest solutions.

3.2.1 Limited Awareness and Information Dissemination

One of the main limitations is the lack of information about PV energy in northern Nigeria that is widely known and disseminated. Solar PV's widespread acceptance is hampered by a lack of public awareness of its advantages, technologies, and applications. Through focused awareness campaigns and educational initiatives, efforts should be made to enlighten the general public, policymakers, and other involved groups (Adeleke, 2018).

3.2.2 Inadequate Regulatory and Policy Frameworks

Investment is hampered, and market uncertainty is caused by the lack of comprehensive regulatory frameworks and insufficient rules for the growth of PV energy. To encourage private investment and PV energy deployment, the government should create clear laws and regulations that offer incentives such as tax rebates, feed-in tariffs, and net metering (Bamigbade et al., 2020).

3.2.3 Limited Access to Funding

The absence of affordable funding is a major impediment to the growth of PV energy in northern Nigeria. Renewable energy projects are frequently viewed by financial institutions as high-risk endeavours, which limits the supply of loans and credit facilities. PV energy project promotion and private sector investment can be increased by establishing specialised financing mechanisms such as green bonds and venture capital funds (Ogbonna et al., 2021).

3.2.4 Weak Institutional Capacity

Northern Nigeria's insufficient institutional capacity for the development of PV energy is a serious problem. Engineers, technicians, and trained professionals with knowledge of PV systems are in short supply. To improve human capital and technical capabilities in the PV sector, investments must be made in training programmes, capacity-building projects, and knowledge transfer partnerships (Kargbo et al., 2020).

3.3 Opportunities

This section examines the potential growth opportunities for photovoltaic (PV) electricity in northern Nigeria. In addition to the area's exceptional solar potential, there are other prospects for increasing PV deployment in the region. Following sub-sections carefully analyses the body of accessible information to identify and elaborate crucial points. The findings are intended to provide policymakers, researchers, and practitioners with new insights on how to make use of the opportunities to promote the expansion of sustainable solar energy in the region.

3.3.1 Increase universal awareness of climate change.

Awareness of the global necessity for renewable energy has surged in recent years. Governments worldwide, including Nigeria, are actively seeking methods to generate power with reduced environmental impact, aiming to benefit both current and future generations. According to UN Secretary-General Antonio Guterres, renewable energy technology should be elevated to the status of a global public good, facilitated by increased knowledge exchange and technology transfer, alongside efforts to minimise intellectual property rights barriers (United Nations Climate Change, 2023).

The United Nations Conference on Trade and Development (UNCTAD) revealed that the top 100 global energy companies are progressively shifting their focus towards renewable energy sources, divesting their fossil fuel assets at a rate of approximately $15 billion per year (UNCTAD, 2023). Furthermore, financial institutions such as the World Bank and the International Finance Corporation have initiated support programs for nations like Ghana, Liberia, and Sierra Leone, following an international commitment made in April 2016 at the UN Headquarters to assist developing nations, particularly those in Africa, in advancing PV power.

Among these initiatives, the World Bank's $220 million Ghana Energy and Development Access Project (GEDAP) stands out as one of the pioneering efforts, aiming to provide universal access to renewable energy through autonomous solar goods and services (World Bank, 2020). Additionally, in early 2023, as part of the African Energy Transition Catalyst (AETC) program, the African Development Bank (AfDB) approved a grant from the Sustainable Energy Fund for Africa (SEFA) totalling $7.88 million. This grant is intended to accelerate the development of renewable energy at both national and regional levels (African Development Bank Group, 2023).

3.3.2 Decrease price of renewable energy and equipment

The rapid decline in the prices of photovoltaic (PV) systems on a global scale can be attributed to several key factors, notably the advancement in Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL), coupled with a decrease in the levelized cost of electricity (LCOE). These factors have made renewable energy technologies, such as wind and solar, more cost-effective compared to traditional fossil fuel technologies, including coal (UN Climate Change, 2023).

An exemplary initiative demonstrating this trend is the SunShot initiative by the United States Department of Energy, which reported a record-low LCOE of $0.036/kWh in 2020 for solar PV systems installed in Daggett, CA. This initiative aims for an even more ambitious reduction to $0.016/kWh by 2030, leveraging the region's abundant solar resource exceeding 6.5 kWh/m^2/day (Office of Energy Efficiency & Renewable Energy, 2021). The solar potential in Daggett, CA, mirrors that found in North-western Nigeria, indicating the feasibility of achieving similar cost reductions in the region.

Furthermore, according to Yu et al. (2019), over the past decade, technological advancements have led to a remarkable decline in the global average price of PV modules by a factor of 79, accompanied by a substantial increase in efficiency from 15% to 25%. These developments bode well for the increased penetration of PV power technology into the energy mix in the near future.

3.3.3 Bridging the gap between electricity generation and demands

Nigeria stands out as one of Africa's rapidly growing nations, yet its power generation capacity has been increasing at a sluggish pace. Over the period from 2005 to 2022, the population witnessed a staggering 59% increase (Macrotrends, 2023), while the average annual capacity of electricity generation remained relatively low at 6,962 GWh (CEIC DATA, 2023). This trend mirrors the situation in many African countries. According to the International Energy Agency's (IEA) World Energy Outlook (2018), a substantial 42% of individuals in Sub-Saharan Africa lack access to the grid, with rural areas facing even greater challenges, with only 16% having access. The absence of electricity in certain parts of Africa severely hampers commercial and educational activities. Hence, tapping into solar resources is deemed critical for bridging this energy gap.

Despite the undeniable advantages of renewable energy sources like solar and wind power, their intermittent nature poses a significant challenge. Fluctuations in sunlight and wind intensity can disrupt grid stability and limit the overall effectiveness of these resources. This is where energy storage technologies come into play, offering a crucial solution for a clean and reliable energy future.

Currently, there exists a diverse range of energy storage technologies, including mature options such as electrochemical, pumped hydro, and compressed air, alongside those still in the research and development phase. Among these, Battery Energy Storage Systems, particularly Lithium-ion batteries, stand out for their high energy density, rapid response times, and scalability (Chen et al., 2020). These systems effectively store surplus renewable energy during peak generation periods, releasing it to meet demand during low-generation periods.

Pumped Hydro Storage is another established technology that harnesses off-peak electricity to pump water uphill into a reservoir, later releasing it through turbines to generate electricity during peak demand periods (IRENA, 2019). With its significant storage capacity and extended discharge durations, pumped hydro plays a pivotal role in ensuring grid stability and reliability.

Compressed Air Energy Storage (CAES) is also gaining traction, storing energy by compressing air into underground caverns during off-peak periods, subsequently releasing it through turbines to generate electricity during high-demand periods (Yang et al., 2022). Although commercially available, CAES technology continues to undergo refinement to enhance efficiency and reduce costs.

Additionally, promising emerging technologies such as flywheels, flow batteries, and thermal energy storage offer unique benefits in terms of cost, efficiency, and suitability for specific applications (Badwal and Jackson, 2014).

The benefits of energy storage technology are profound. Not only does it facilitate improved grid integration by smoothing out fluctuations in renewable energy generation, but it also enables a higher penetration of renewable energy sources into the overall energy mix, thereby accelerating the transition towards sustainability (Hirsh et al., 2011). Moreover, by reducing dependence on fossil fuels for backup power generation, energy storage contributes to lower greenhouse gas emissions and reduced air pollution (Fife and Rai, 2018).

However, despite these benefits, the upfront cost of energy storage systems remains a significant barrier to widespread adoption (Schmidt et al., 2017). Continued research and development efforts are imperative to driving down costs and improving the economic viability of energy storage, thus paving the way for a more sustainable and resilient energy future.

3.3.4 Removal of fuel subsidy and its ramifications

One of the most significant financial allocations for administrative governments worldwide revolves around fossil fuel subsidies. In 2020 alone, the global fossil fuel industry received an astounding $5.9 trillion in subsidies, serving as a substantial financial hurdle hindering the transition to renewable energy (United Nations Climate Change, 2023). Achieving the Sustainable Development Goals (SDGs) by 2030 poses another substantial challenge, particularly for developing countries, which currently grapple with an annual investment deficit of nearly $4 trillion in Foreign Direct Investment (FDI) (UNCTAD, 2023).

The International Energy Agency (IEA) emphasised in 2018 that government-driven energy investment accounts for over 70% of global energy investment. Consequently, the message is clear: the world's energy future hinges on decisions and policies formulated by governments (IEA, 2018). Prior to their discontinuation in early 2023, fossil fuel subsidies in Nigeria had reached a staggering level of around $7 billion annually (Bloomberg, 2023). This signals the end of the subsidy era, necessitating appropriate policies and a genuine commitment within Nigeria's energy sector to propel the country towards achieving the SDGs by 2030.

In essence, the abolition of fossil fuel subsidies presents an opportunity for Nigeria to redirect financial resources towards renewable energy initiatives and align its energy policies with broader sustainable development objectives. With strategic planning and decisive action, Nigeria can leverage this pivotal moment to accelerate its transition towards a more sustainable and resilient energy future.

3.4 Treats

This section delves into the various threats that could impede the successful implementation and proliferation of PV energy in Norther region. Understanding these threats can help in formulating strategies to overcome the said challenges.

3.4.1 Deficit in Technical Skill and Capacity Building

The development and integration of Photovoltaic (PV) systems into the energy infrastructure of Northern Nigeria can only be realised with the requisite technical skill set and capacity building among local interested parties. One of the fundamental challenges hindering the rapid adoption of PV technology in the region is the scarcity of skilled technicians, engineers, and professionals well-versed in the design and maintenance of solar energy systems (Amir and Khan, 2022). For PV systems to operate optimally, installations must adhere to specific standards, and regular maintenance is vital. However, in many parts of Northern Nigeria, there's a pronounced deficit in training institutions and programs that specialise in renewable energy technologies (Eshiemogie, Ighalo and Banji, 2022). This deficit not only impacts the installation phase but also the operational phase, as poorly installed or maintained PV systems can suffer from inefficiencies, reducing their power output and overall lifespan.
Moreover, local communities often lack the understanding and expertise to conduct basic troubleshooting or preventive maintenance on their PV installations. As a result, when minor technical hitches arise, they can escalate into more significant problems, leading to prolonged downtimes or even permanent damage to the PV systems.

3.4.2 Economic instabilities

Economic instabilities, particularly pronounced in developing countries like Nigeria, have significant implications for the adoption and feasibility of Photovoltaic (PV) systems. A critical aspect of this instability is currency volatility. As local currencies fluctuate, especially when declining against major global standards, the consequences for renewable energy become clear. Import costs for essential PV components, from solar panels to inverters, can significantly increase. These added costs often get passed on to end-users, potentially making renewable energy solutions more costly and less appealing (Hazelton, Bruce and MacGill, 2014).

Coupled with currency concerns is the challenge of inflation. As inflation rates rise, the purchasing power of residents diminishes, affecting various sectors of the economy. Higher inflation can increase the prices of local goods, services, installation, and maintenance of PV systems for the renewable energy sector. Households and businesses, already navigating limited financial resources, might find it difficult to allocate funds for renewable energy solutions, which, though promising long-term benefits, require a significant initial investment (Islam, Islam and Begg, 2008). Such economic uncertainties impact consumers and resonate with the investment community. An unstable economic environment, characterised by unpredictable financial scenarios, can cause domestic and international investors to reconsider. With its need for substantial capital investment and extended return-on-investment timelines, the renewable energy sector might be seen as a riskier venture amidst such uncertainties (Rahman et al., 2023).

These economic challenges also influence the financing landscape. Traditional financial institutions operating within this unpredictable environment might adopt a more guarded approach. As a result, potential borrowers looking for funds for PV installations could face high-interest rates, stringent lending criteria, and shorter loan durations, complicating the financial aspect of PV system adoption (Hafner and Tagliapietra, 2020).

Another critical area influenced by economic challenges is the supply chain. Economic downturns or disruptions can impact established supply chains, leading to delays in securing vital components for PV systems. These disruptions can increase project costs and prolong project timelines, making some projects less feasible and deterring potential investors (Franco and Groesser, 2021).

Lastly, the interplay between economic realities and governmental policies is crucial. Economic pressures push governments to re-assess their financial strategies, which may sometimes mean reducing or eliminating subsidies and incentives for the renewable sector. Such policy changes can shift the competitive landscape, potentially favouring conventional energy sources over PV systems (Bulkeley et al., 2022).

3.4.3 Environmental

Northern Nigeria, being predominantly arid and semi-arid, is endowed with abundant sunlight throughout the year, making it an ideal region for solar energy generation, as earlier highlighted. However, this geographical positioning also exposes the region to environmental challenges that can impact the performance of Photovoltaic (PV) systems. Prominent among these challenges are dust and sandstorms. Dust and sand particles can settle on the surface of solar panels, creating a layer that obstructs sunlight penetration. This obstruction can significantly reduce the efficiency of the panels, as it curtails their capacity to absorb sunlight and convert it into electricity (Diop et al., 2020). Over time, and without proper maintenance, this accumulated dust and sand can lead to permanent damage, reducing the lifespan of the panels. Additionally, sandstorms, a common phenomenon in arid regions, can have abrasive effects on the protective coatings of solar panels. The forceful impact of wind-blown sand particles might lead to micro-scratches, which can further diminish the overall performance of the PV systems (Short et al., 2018).

3.4.4 Security

Due to the inherent geographical isolation of numerous off-grid projects, the logistical aspects and transportation of equipment to installation sites may be susceptible to security breaches, including attacks or theft. Furthermore, it is essential to note that maintenance personnel and installation teams encounter increased levels of risk while operating in such environments. The aforementioned security problems have the potential to result in escalated operational expenditures. According to Adewale and Olugbenga (2022), the implementation of protective measures, the increase in insurance premiums, and the potential occurrence of project delays or suspensions due to security concerns can contribute to the escalation of project expenses. The perceived security dangers may also deter potential investors from providing financial support to off-grid ventures. This presents a significant challenge as off-grid solutions play a critical role in improving energy accessibility in regions that investors may perceive as high-risk (Williams, 2023).

4 Interdependencies and the Way Forward

The advancement of solar photovoltaic (PV) technology in Northern Nigeria requires a comprehensive approach that considers the complex interactions between economic, environmental, and security factors. This section introduces a strategic outline that will later delve into these interdependencies, crucial for promoting solar PV adoption. The forthcoming discussion will detail essential measures including raising public awareness about solar energy, developing mini-grid infrastructure, providing professional training, and using micro-grid systems to test and refine policy frameworks. These steps form a multi-faceted strategy aimed at creating a resilient and sustainable solar energy landscape in the region.

4.1 Promote public awareness campaigns on solar energy potentials and market prospects.

To address the unique energy challenges faced in northern Nigeria, concerted efforts from academic communities, non-governmental organizations (NGOs), and both public and private climate change activists are essential in leading a comprehensive public awareness campaign on solar photovoltaic (PV) energy adoption in the region. This initiative is particularly crucial in light of sporadic power supply, frequent grid outages, and the prevalent issue of energy poverty. Local contributors must play an active role in identifying areas with urgent energy needs and tailoring solutions to address them effectively. Studies such as the one conducted by Nwokocha et al. (2018) shed light on the importance of PV awareness, attitudes, and expected benefits through qualitative surveys across Nigeria's 36 states. It is evident that a lack of public awareness and information dissemination significantly hampers the widespread adoption of PV energy. Furthermore, drawing attention to solar PV financing solutions accessible to households and businesses, in collaboration with microfinance institutions, can alleviate the initial launch costs and facilitate broader adoption. Encouraging individuals and companies that have already embraced solar PV to share their positive experiences can significantly influence adoption rates, as recommendations from peers hold considerable sway.

A steady flow of information must be maintained through various channels, including social media platforms, radio broadcasts, and community meetings, to ensure the public remains informed about the latest advancements in solar PV technology and market opportunities. Additionally, monitoring and evaluation measures should be established to track the effectiveness of awareness initiatives regularly. Empirical evidence, such as the number of installations, energy savings achieved, and client satisfaction levels, can be used to gauge the success of these efforts and inform future strategies. By fostering collaboration among key players, leveraging financing mechanisms, and implementing robust awareness campaigns, northern Nigeria can accelerate the adoption of solar PV energy, ultimately contributing to enhanced energy security, economic development, and environmental sustainability in the region.

4.2 Development of mini grid infrastructure to support distributive solar generation.

The development of mini grid infrastructure to support distributive solar generation in Northern Nigeria holds significant promise in addressing the region's energy access, reliability, and sustainability challenges. Distributed solar generation, characterised by independent systems for energy generation and distribution, offers a viable solution to provide safe and dependable energy to numerous remote settlements (da Silva et al., 2019).

Mini grid systems, which encompass small-scale electricity generation and distribution networks, are particularly well-suited for the northern region's diverse energy needs. These systems can be incrementally expanded by adding solar panels and storage units as energy demands increase, ensuring scalability and adaptability to various clusters of energy demand (Wang et al., 2020).

Integration of modern control mechanisms enables real-time monitoring and remote management of mini grid systems, ensuring reliable operation and efficient energy distribution. This technological advancement enhances the resilience of the mini grid infrastructure, allowing for prompt response to fluctuations in energy demand and supply (Stephanie et al., 2024). The deployment of PV solar mini grid systems offers several benefits to host communities in Northern Nigeria. Firstly, it creates opportunities for job creation and local economic development, as skilled labour is required for installation, operation, and maintenance of the infrastructure (Damo et al., 2024). Additionally, mini grid projects empower communities by providing them with greater control over their energy resources and reducing dependence on centralised utility grids (Bamisile, 2017). Moreover, the transition to solar energy contributes to environmental sustainability by reducing noise and air pollution associated with the use of fossil fuel generators (Obada et al., 2024).

By investing in the development of mini grid infrastructure to support distributive solar generation, Northern Nigeria can unlock its renewable energy potential, improve energy access for remote communities, and foster sustainable economic growth and environmental conservation in the region.

4.3 Provision of on-the-job training for certified professional

The promotion of solar PV (photovoltaic) adoption in northern Nigeria and the expansion of the solar energy business in the region can significantly benefit from the provision of on-the-job training for qualified experts. On-the-job training equips qualified professionals with the precise abilities and information required for solar PV installation, maintenance, and troubleshooting (Sooriyaarachchi et al., 2015). This practical knowledge is crucial for ensuring that solar PV systems are installed correctly and operate effectively, thereby enhancing their dependability, endurance, and overall performance (Sarmento et al., 2018).

By providing comprehensive on-the-job training, the likelihood of problems or malfunctions that could deter potential users from investing in solar PV systems is significantly reduced (Manwell et al., 2015). When consumers and businesses have confidence in the skills and expertise of the professionals who install and maintain solar PV systems, they are more inclined to invest in the technology. Certified and trained professionals inspire trust in both the technology itself and the broader solar energy industry, thereby fostering greater adoption and acceptance (Aliyu, Modu and Tan, 2021) .

Effective collaboration between government organisations, educational institutions, trade associations, and solar enterprises is essential for efficiently promoting the adoption of solar PV through on-the-job training programs (Abdullahi et al., 2022). Financial incentives, subsidies, or certification programs can encourage more professionals to enrol in training programs and obtain certification as solar PV experts (Suehiro et al., 2019). Moreover, consumer and company education campaigns and outreach initiatives play a crucial role in informing them about the benefits of engaging trained experts for their solar PV projects, thereby further encouraging adoption (Ifeoma, et al., 2024).

4.4 Adoption of existing micro grid PV system as testbed for trial-testing of regulatory and policy frameworks

To facilitate the uptake of PV systems in northern Nigeria, leveraging existing mini-grid PV systems as testbeds for regulatory and legislative frameworks proves to be a strategic approach. This tactic aligns with the principles of adaptive management, allowing policymakers and regulators to iteratively refine policies based on real-world feedback and experiences (Reyers et al., 2018). Selecting an appropriate mini-grid system for the testbed is paramount to ensure its representativeness of the broader environment. Factors such as location, size, technology, and ownership structure should be considered to accurately reflect typical scenarios prevalent in northern Nigeria (Duran and Sahinyazan, 2021).

Moreover, the regulatory structure governing mini-grid PV systems must be tailored to address the unique characteristics and challenges of these systems. This entails the development of comprehensive frameworks covering aspects such as licensing, tariffs, technical standards, and quality control (Berizzi et al., 2019). To incentivise private sector investment in mini-grid PV plants within the testbed, policymakers can explore various mechanisms such as tax credits, subsidies, or feed-in tariffs. These incentives serve to mitigate financial risks and enhance the attractiveness of investment opportunities (Akinyele, Belikov and Levron, 2018).

Establishing robust data gathering mechanisms within the testbed is crucial for monitoring the performance of mini-grid PV systems. Continuous monitoring of energy production, consumption trends, and client satisfaction enables involved groups to make informed decisions and adjustments (Justo and Mishi, 2020). Furthermore, incorporating feedback loops into the regulatory framework allows beneficiaries, including mini-grid operators and customers, to provide input and suggestions based on their experiences. This iterative process fosters a participatory approach to policy development, ensuring that regulations are responsive to the evolving needs and dynamics of the sector (Chatterjee, 2020).

By utilising an actual mini-grid PV system as a testbed, policymakers and regulators can gain invaluable insights into the opportunities and challenges associated with solar mini-grids in northern Nigeria. Leveraging successful experiences and lessons learned from the testbed, policymakers can then refine regulatory and legislative environments to accelerate PV penetration in the region (Adaramola and Vagnes, 2015). Employing mini-grid PV systems as testbeds for regulatory and legislative frameworks offer a pragmatic and effective strategy for driving PV uptake and fostering sustainable energy development in northern Nigeria.

5 Discussion

The prospects for integrating solar PV into Nigeria's energy system are promising, driven by several key factors. Firstly, Nigeria enjoys abundant solar resources, characterised by high solar irradiance levels, making it an ideal candidate for generating clean electricity through solar panels (SEforAll, 2022). This abundance presents an opportunity to reduce reliance on fossil fuels and mitigate their associated environmental costs, contributing to a more sustainable energy future. Moreover, solar PV systems offer the flexibility of decentralised generation, with the capability to be deployed at various scales ranging from large-scale solar farms to rooftop installations on homes and businesses. This decentralised approach not only promotes energy security but also extends access to electricity to remote areas that are not connected to the national grid, thus bridging the energy access gap (Bamisile, 2017).

Additionally, solar PV holds potential for powering Power-to-X (PtX) technologies, such as hydrogen production. By providing clean electricity for PtX processes, solar PV enables the production of green hydrogen, which can be utilised in various sectors including transportation and industrial processes, thereby facilitating sector coupling and decarbonisation efforts (Sorrenti et al., 2022).

To fully realise these prospects, it is essential to address challenges related to grid stability, demand-supply balancing, and integration of solar PV into the existing grid infrastructure. Smart grid technologies and demand-side management strategies can play a crucial role in mitigating these challenges and optimising grid stability (Adaramola et al., 2019). Strategic decision-making and planning are necessary to ensure seamless integration of large-scale solar PV into the grid, enhancing power flows and overall system reliability (Oyedepo et al., 2020). A clear and easy-to-follow methodological framework for conducting techno-economic analysis, such as the one proposed by Ahmed et al. (2024), can assist in focusing efforts related to the technical and economic evaluation of energy retrofit technologies onto meaningful indicators with relevant real-world interpretation for key stakeholders. This approach can provide policymakers with better insights into the deployment and scale-up of solar PV technologies to achieve net zero targets.

Furthermore, policy and financing mechanisms play a pivotal role in promoting widespread adoption of solar PV. Governments should incentivise solar PV deployment through measures such as feed-in tariffs and tax breaks, which can stimulate investment and accelerate the transition to solar energy (AbdulQadir et al., 2021). Additionally, concerted efforts are needed to establish smooth financing mechanisms and implement supportive government policies to facilitate the deployment of solar PV across Nigeria.

6 Conclusion

The challenges and prospects of photovoltaic (PV) systems in Northern Nigeria are characterised by an intricate web of economic, environmental, and security considerations. In confronting these challenges, there is a clear path forward that capitalises on the region's abundant solar potential while acknowledging the nuanced barriers to adoption. Economic instabilities underscore the need for innovative financing and policy support to make PV technology accessible amidst currency volatility and inflation. Environmental factors, particularly dust and sandstorms, necessitate robust maintenance and protective measures to ensure the longevity and efficiency of solar installations. Security issues demand strategic planning and investment in safeguarding infrastructure and personnel involved in the deployment of solar energy solutions.

The advancement of solar energy in Northern Nigeria requires a holistic and integrated approach, which has been outlined through several strategic initiatives. Public awareness campaigns are essential to shift perceptions and garner support for solar technology. The development of mini-grid infrastructure promises to enhance energy access and reliability, while the provision of on-the-job training for professionals aims to build local capacity and expertise. Furthermore, utilising existing micro-grid PV systems as testbeds offers a practical means to refine regulatory and policy frameworks, ensuring they are conducive to the growth of solar energy in the region.

The significance of these actions is profound. For instance, the implementation of mini-grid systems could drastically improve energy access in Northern Nigeria, where a significant portion of the population remains off-grid. Drawing from the World Bank's report, which highlights a less than 60% electrification rate in rural areas of sub-Saharan Africa, the deployment of solar mini grids in Northern Nigeria has the potential to exceed regional benchmarks by providing reliable electricity to remote communities, thereby closing the access gap significantly. Similarly, the emphasis on capacity building through professional training aligns with the International Renewable Energy Agency's (IRENA) findings that skill development is a critical factor for the success of renewable energy projects. By training local professionals, Northern Nigeria could elevate its workforce readiness above the current sub-Saharan African average, ensuring a steady supply of skilled labour necessary for the sustainable expansion of its solar energy sector. Furthermore, utilising existing micro-grid PV systems as experimental sites offers a tangible method to refine policies and regulations. This approach could lead to an enhanced regulatory environment that supports solar energy growth, aiming to surpass the achievements of similar initiatives in regions like East Africa, where regulatory advancements have spurred significant solar market growth.

Overall, the path forward for Northern Nigeria's solar energy landscape lies in embracing these interconnected strategies, fostering a conducive environment for PV adoption, and leveraging the region's solar potential to its fullest. By addressing the economic, environmental, and security challenges through coordinated efforts, Northern Nigeria can transform its energy sector, promote sustainable development, and improve the quality of life for its residents.

Credit Authorship Contribution

Anas A. BisuL Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - original draft; and Writing - review & editing. Tariq G. Ahmed: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - original draft; and Writing - review & editing. Umar S. Ahmad: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - original draft; and Writing - review & editing. Abubakar D. Maiwada: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing - original draft; and Writing - review & editing.

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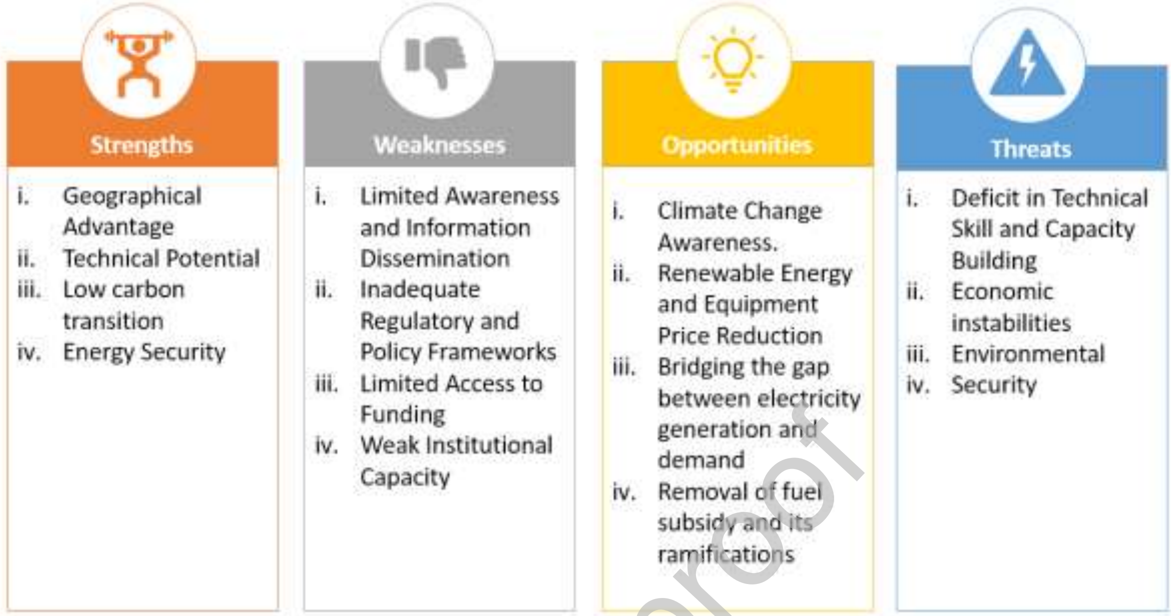
Graphical Abstract



Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: