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AN INVESTIGATION OF THE ECONOMIC, INSTITUTIONAL, TECHNICAL AND FIRM-SPECIFIC DETERMINANTS OF SOLAR ENERGY ADOPTION AMONG SMES IN THE NORTH-CENTRAL REGION OF NIGERIA

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ABSTRACT

The persistent electricity deficit in Nigeria has compelled many Small and Medium Enterprises (SMEs) to explore alternative energy sources. This study an investigation of the economic, institutional, technical and firm-specific determinants of solar energy adoption among (SMEs) in the north-central region of Nigeria using a mixed-methods design. A structured survey was administered to 900 SMEs and 200 key stakeholders (solar vendors, finance providers, and government officials). Quantitative data were analyzed using logistic regression, ordered probit, chi-square, and OLS models, complemented by qualitative insights from stakeholder interviews. The findings reveal that firm size, sector, awareness of government incentives, financing accessibility and perception of reliability are statistically significant predictors of solar energy adoption. Cost of installation and maintenance barriers were also negatively correlated with uptake. Policy recommendations emphasize the need for targeted financing models, incentive awareness campaigns, and supportive regulatory frameworks to drive energy transition among SMEs.

KEYWORDS: Solar energy, SMEs, energy transition, North-Central Nigeria, logistic regression, OLS, ordered probit, renewable energy adoption.

INTRODUCTION

Nigeria is located on the western coast of Africa and features a diverse geography, ranging from arid to humid equatorial climates. The country is richly endowed with natural resources, including large deposits of petroleum, natural gas, minerals, and other energy resources (Udebunu, 2011). Geographically, Nigeria spans latitudes 4.32°N to 14.1°N and longitudes 2.72°E to 14.64°E, covering a land area of approximately 924,000 km^2 with a population of about 223 million people (NPC, 2023). A significant portion of the population resides in rural areas, where access to electricity is often limited (Arowolo et al., 2019). Consequently, many rural households rely on petrol and diesel generators, charcoal, and kerosene lamps for lighting. These methods present multiple challenges, including high fuel costs, fuel scarcity, and maintenance issues (Ogbuabor et al., 2018). Additionally, poor road infrastructure, particularly during the rainy season when roads are frequently flooded, further complicates the transportation of fuel for generators (Ohimain & Izah, 2016).

Alternative lighting sources, such as candles, charcoal, and kerosene lamps, pose serious health and environmental risks. Despite these challenges, Nigeria remains the leading oil producer in Africa and ranks as the 13th largest globally, with an average daily production of 2.5 million barrels (Udebunu, 2011). The country also holds the second-largest oil reserves in Africa and the sixth-largest worldwide, with approximately 90% of its economy reliant on crude oil (Ohimain, 2016). However, the oil sector has been undermined by corruption, theft, and oil spills, yet it continues to serve as the primary source of foreign earnings and export revenue (Orji, 2014).

Energy is a critical driver of economic growth, social equity, and environmental sustainability (World Bank, 2000; United Nations, 2000, 2004; UNDP, 2003). Ensuring access to modern, clean, and affordable energy is a key challenge for countries transitioning toward sustainable development (IEA, 2016). For developing nations, access to modern energy services yields significant benefits, including economic growth, poverty reduction, improved health, and enhanced productivity (IEA, 2016). The IEA emphasizes that breaking the cycle of energy poverty and underdevelopment requires governments to improve the availability and affordability of modern energy services (IEA, 2004; UN, 2012). Although no single definition of modern energy access exists, it typically encompasses three forms of energy, each contributing substantially to social and economic development (IEA, 2016). At a minimum, electricity should be available to power household lights and appliances as well as essential public facilities such as schools, hospitals, and government offices.

Mechanical power from electricity or other energy sources is vital for productive economic activities, including agriculture, industry, and small-scale businesses, as well as for providing cleaner, safer cooking and heating solutions. In Nigeria, innovative off-grid solar initiatives are increasingly deployed, particularly in rural areas that remain underserved by the national grid.

These communities often rely on costly and environmentally damaging alternatives such as diesel generators due to slow grid expansion and logistical and financial constraints, despite the country's abundant renewable energy potential. Nevertheless, Nigeria faces persistent challenges in power generation, including unreliable gas supply, aging and poorly maintained infrastructure, and inefficient transmission and distribution networks. Expanding electricity generation capacity is therefore essential to meet the rising demand of a rapidly growing population. Among renewable energy sources, hydropower is currently the only large-scale source connected to the national grid, contributing about one-fifth of total installed capacity, although only 14% of this is utilized (NEP, 2023). Wind energy has potential but remains largely untapped, while solar energy offers exceptional prospects due to high daily sunlight, ranging from 3.5 hours at the coast to nine hours in northern regions, with direct normal irradiance between 4.1 and 5.0 kWh/m^2 (REN21, 2018). Solar power adoption is gradually increasing through photovoltaic and concentrating solar power systems, supporting rural electrification, healthcare, water supply, and education (Olayinka et al., 2017; Emmanuel et al., 2021).

Off-grid solar solutions, including standalone systems, mini-grids, and solar home systems, provide decentralized, renewable, and sustainable energy, helping to address electricity access gaps in rural and semi-urban areas. By reducing reliance on fossil fuels, these systems also mitigate environmental impacts such as deforestation and greenhouse gas emissions. Access to electricity via off-grid solar promotes socio-economic development by powering productive activities, extending work and study hours, improving education and health outcomes, supporting irrigation and food security, and enabling entrepreneurship and job creation. Energy poverty in Nigeria remains closely linked to low household income and reliance on traditional biomass, limiting social and economic productivity. Expanding access to modern energy services can break this cycle, enhancing productivity, livelihoods, and overall development (IEA, 2016; Okoye & Okenwa, 2022). Given the country's persistent electricity deficit, off-grid solar systems present a practical, scalable, and sustainable solution to meet the energy needs of underserved communities while supporting climate goals and national development objectives.

Small and Medium Enterprises (SMEs) are a crucial component of Nigeria's economy, representing over 80% of all businesses and playing a significant role in employment creation and GDP growth (SMEDAN, 2021). In the North-Central states—including Benue, Kogi, Kwara, Nasarawa, Niger, and Plateau—SMEs operate across diverse sectors such as agro-processing, manufacturing, hospitality, and services. Despite their economic potential, these businesses face major operational challenges, primarily due to unreliable electricity supply, which compels many to depend on petrol or diesel generators (Oladipo & Akinwale, 2023). This reliance elevates operational costs, reduces profitability, and constrains competitiveness.

Solar energy, as a renewable and sustainable power source, presents a viable alternative. Nigeria's geographic location ensures abundant sunlight, with the North-Central region receiving an average daily solar irradiation of 5.5–7.0 kWh/m^2 (Nigerian Meteorological Agency [NiMet], 2022). Globally, the adoption of solar energy has been facilitated by falling technology costs, favorable policies, and growing environmental awareness (REN21, 2023). However, uptake among Nigerian SMEs remains limited due to high initial costs, inadequate technical expertise, restricted financing options, and concerns over reliability (Ogunleye & Isola, 2021).

Identifying the factors that influence solar energy adoption among SMEs in the North-Central region is essential for developing targeted interventions, promoting sustainable business practices, and strengthening energy security. Previous studies have highlighted determinants such as cost- benefit considerations, access to finance, awareness, perceived ease of use, government incentives, and environmental consciousness (Adewuyi & Awodumi, 2020; Ibrahim et al., 2022). Yet, empirical research addressing the specific socio-economic and infrastructural context of SMEs in this region is limited. Furthermore, Energy access remains a critical challenge in Nigeria, where power supply inadequacies constrain industrial growth and business competitiveness. SMEs, which contribute over 48% to Nigeria's GDP and account for 96% of businesses (SMEDAN, 2023), are particularly vulnerable to frequent power outages. The rising cost of diesel and unstable grid supply have intensified the search for sustainable alternatives such as solar energy.

Despite increasing awareness of renewable energy solutions, the adoption rate among SMEs in Nigeria remains low (Akinwale & Oladipo, 2022). Understanding the determinants that drive or hinder solar utilization is crucial for developing policies that promote clean energy transitions and business resilience. This study, therefore, examines the economic, institutional, technical, and firm-specific determinants of solar energy adoption among SMEs in the North-Central region of Nigeria, which includes Benue, Kogi, Kwara, Nasarawa, Niger, and Plateau States.

Literature Review

Background Context on Nigerian's Energy System

Access to electricity remains a critical challenge in many rural areas of Nigeria, where a large proportion of the population lacks reliable energy sources. Off-grid solar energy systems have emerged as a promising solution, providing sustainable, decentralized power generation. This literature review explores the potential of off-grid solar technology to improve electricity access in underserved rural communities, drawing on both local and international experiences.

Nigeria is richly endowed with diverse energy resources, positioning it as one of the most resource- abundant countries in Sub-Saharan Africa. If effectively harnessed, these resources could provide sustainable energy security and a diversified energy mix capable of meeting both domestic and industrial energy needs. The country possesses the continent's largest natural gas reserves and is a major oil producer. As of 2021, Nigeria's crude oil reserves were estimated at 36.22 billion barrels, while natural gas reserves stood at approximately 197 trillion standard cubic feet (SCF) (Energy Commission of Nigeria, 2019). Despite these resources, inadequate infrastructure, operational inefficiencies, and socio-political challenges in the Niger Delta have limited the country's ability to fully exploit its oil and gas potential (Oyedepo, 2012). Limited investments in gas processing and distribution have also constrained the use of natural gas, although expanding this sector could help address energy deficits while supporting cleaner energy production through gas-to-power initiatives.

Nigeria also has coal and lignite reserves estimated at 2.735 billion tonnes. Although coal was historically used for power generation in the 1950s, its utilization has declined over time (Aliyu et al., 2013). Renewed interest in coal is driven by its potential to diversify the energy mix, though environmental concerns regarding its carbon footprint pose significant challenges. Hydropower is the largest renewable energy source in Nigeria, contributing approximately 35.6% to the national electricity mix (Lawal & Adeoti, 2021). The country operates three major hydropower plants with a combined installed capacity of 1,900 MW and has potential for over 13,000 MW from large- scale and 3,500 MW from small-scale hydropower systems (Sambo, 2009). However, seasonal water variability and limited infrastructure have constrained the full utilization of hydropower resources.

Solar energy is abundant in Nigeria due to its tropical location, with average solar radiation ranging from 3.5 to 7.0 kWh/m²/day (Sambo, 2009). This potential could generate over 1,850 TWh annually, far exceeding current grid consumption. Yet, solar power accounts for less than 1% of Nigeria's electricity supply, hindered by high initial costs, limited technical expertise, and a lack of incentives for large-scale deployment (Shaaban & Petinrin, 2014). The northern regions also possess moderate wind energy potential, with average wind speeds between 2.0 and 4.0 m/s at 10 meters height (Sambo, 2009), suitable for small-scale wind farms to power rural communities. However, wind energy remains largely undeveloped due to inadequate assessment and limited investment.

Additionally, Nigeria has substantial biomass resources, including agricultural residues, animal waste, and forest products. Biomass potential is estimated at 1.1 million hectares of forest and woodland that could be converted to fuelwood or biogas (ECN, 2019). Crop residues from the agricultural sector also represent a significant bioenergy resource, though biomass utilization remains minimal. Overall, Nigeria's energy resource base is vast and diverse, presenting opportunities for both fossil fuel and renewable energy development. Realizing this potential, however, requires strategic investments in infrastructure, technology, and policy frameworks to support sustainable energy production and distribution.

The use of solar energy as an alternative power source has become a key approach to mitigating Nigeria's persistent electricity shortages. Solar energy involves capturing sunlight to generate electricity or heat, typically through photovoltaic (PV) panels or solar thermal systems (IEA, 2023). For Small and Medium Enterprises (SMEs) in North Central Nigeria, solar energy presents a viable solution to unreliable grid electricity, supporting continuous business operations, reducing costs, and promoting environmental sustainability (Okeke & Nwankwo, 2022). The factors influencing solar energy adoption among SMEs are multifaceted, encompassing economic considerations (installation costs, access to financing), technical aspects (system reliability and maintenance), policy-related issues (government incentives and regulatory frameworks), and socio-cultural dimensions (awareness, perceptions, and trust in the technology) (Adeleke et al., 2021).

Solar energy utilization among SMEs is influenced by multiple interrelated factors, including:

1. **Firm Attributes:** Size, age, and sector type affect capital availability and energy needs (Olawale & Garba, 2023).
2. **Economic Factors:** Cost of installation, financing access, and expected returns on investment determine affordability (Eberle & Mensah, 2022).
3. **Institutional Context:** Awareness of incentives, regulatory frameworks, and government policies influence adoption (Yahaya & Tella, 2023).

Technical Perceptions: Reliability of systems, maintenance access, and availability of skilled technicians shape confidence in solar solutions (Ikechukwu et al., 2021).

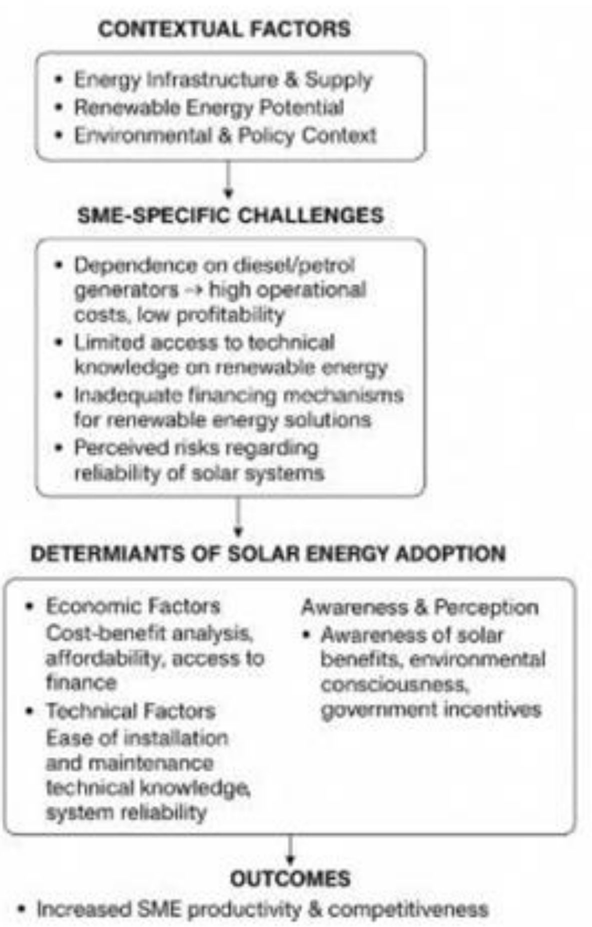

Figure 1: Contextual Factors.

Theoretical Background

This study used **Diffusion of Innovation Theory (Rogers, 2003)** and **Technology Acceptance Model (TAM)** as its main theoretical anchors.

1. **Diffusion of Innovation Theory** explains how new technologies spread within a social system over time, emphasizing factors such as relative advantage, compatibility, complexity, trialability, and observability (Mwangi & Akinlabi, 2019).
2. **Technology Acceptance Model (TAM)** suggests that **perceived usefulness** and **perceived ease of use** are critical predictors of adoption behavior (Davis, 1989; updated perspectives in Olamide & Yakubu, 2020). TAM posits that perceived usefulness and ease of use determine technology adoption. Rogers' theory.

These models are relevant because solar technology adoption by SMEs is influenced not only by cost–benefit analyses but also by perceived technological suitability and social influences. emphasizes that awareness, trialability and relative advantage influence diffusion rates; applicable to solar technologies among SMEs.

Empirical Review

Studies on the Nigeria Power Sector

The Nigerian power sector has faced persistent challenges over many years, largely due to historical corruption that has impeded its development. Studies identify corruption as a major constraint on the country's socio-economic progress over the past two decades (Sambo et al., 2012). Corruption, defined as the "abuse of entrusted power for private gain," has not only hindered development but also created an environment of uncertainty that discourages investment in the power sector and across sub-Saharan Africa (Obuah, 2010). Research also highlights the heavy reliance on natural gas in Nigeria's grid system as a key issue, with frequent power outages often linked to inadequate gas supply for electricity generation (Gatugel et al., 2015). Furthermore, insufficient maintenance has left much of the grid infrastructure outdated and largely non- functional (Alao & Awodele, 2018). In response, the Nigerian government has implemented Power Sector Reforms aimed at reducing energy shortages, improving electricity efficiency, and diversifying energy sources (Imam, Jamasb, & Liorca, 2019).

Renewable Energy Development

Ang et al. (2015) explain that renewable energy originates from virtually inexhaustible sources such as solar, wind, and geothermal power. It is favored for its sustainability and lower environmental impact compared to nonrenewable sources, though capturing and storing such energy efficiently requires advanced technologies (Twidell & Weir, 2015). Solar energy, in particular, offers advantages due to its low maintenance requirements and ease of use. Among renewable sources, solar power is especially convenient because it can be deployed close to points of consumption, unlike wind or geothermal energy. However, solar energy can be limited in regions with reduced sunlight during winter (Akinyemi et al., 2012). In contrast, Nigeria enjoys abundant year-round sunlight, providing substantial opportunities to generate reliable and sustainable electricity.

Solar power is considered one of the most promising clean energy technologies due to its virtually limitless potential (Emodi & Boo, 2015). It can be harnessed using photovoltaic (PV) cells, solar thermal systems, and photosynthesis-based methods, offering a cost-effective and environmentally friendly energy option for both residential and commercial use (Riti & Shu, 2016). Despite Nigeria's chronic power supply challenges, renewable energy—particularly off-grid solar—has not yet received sufficient attention from the federal government and private sector (Nwokocha et al., 2018). Average solar radiation in Nigeria is estimated at 19.8 MJ/m^2 per day, with 6–7 hours of sunshine daily. If fully exploited, this solar potential could generate approximately 1,850,000 GWh of electricity annually (Riti & Shu, 2016).

It has been suggested that the Nigerian Electricity Regulatory Commission (NERC) and the Energy Commission of Nigeria (ECN) should work closely to supervise initiatives like the Center for Energy Research, ensuring effective monitoring and positive outcomes. Current solar energy applications in Nigeria include solar thermal systems for cooking, PV water pumping, solar- powered refrigeration in rural clinics, and solar traffic lights. Several studies (World Economic Forum, 2013; Twidell & Weir, 2015; Riti & Shu, 2016; Somefun et al., 2020) highlight that solar energy offers significant benefits with relatively few drawbacks compared to other renewable sources in Nigeria. Additionally, Aliyu et al. (2015) note that repeated failures of conventional electricity systems have had serious socio-economic consequences, emphasizing the urgent need for alternative and sustainable energy solutions.

Status of Off-Grid Solution in Nigeria

The off-grid solar energy sector in Nigeria presents both considerable challenges and significant opportunities, as highlighted in the Renewable Energy Roadmap (2023). Currently, around 57% of Nigerians lack access to electricity, with rural and underserved areas most affected. Many households and small businesses rely heavily on expensive and polluting diesel generators to meet their off-grid energy needs. Nigeria is endowed with abundant solar resources, with average annual global horizontal irradiation ranging from 1,600 to 2,200 kWh/m², and the highest regions exceeding 2,000 kWh/m². This makes distributed solar photovoltaic (PV) systems a highly feasible option for off-grid electrification. There is also potential for small-scale hydro and biomass solutions to address specific rural energy requirements.

To promote off-grid renewable energy, the government has introduced several initiatives. These include the Rural Electrification Strategy and Implementation Plan (RESIP), developed in collaboration with the private sector to deploy solar mini-grids and home systems. The National Renewable Energy Action Plan (NREAP) also sets clear targets for off-grid renewable capacity expansion.

Despite these efforts, several barriers hinder deployment. Renewable energy technologies often have high upfront costs compared to conventional generators, and financing options for households and small enterprises are limited. Additionally, rural communities frequently lack awareness and technical capacity to adopt and maintain these systems.

Moving forward, accelerating the deployment of solar mini-grids and home systems is critical. Innovative financing mechanisms, such as microfinance and blended finance models, can reduce initial investment burdens. Promoting decentralized renewable energy adoption can improve reliability, affordability, and energy access.

The potential for off-grid solar energy to transform electricity access in rural Nigeria is substantial. Despite being Africa's largest oil and gas producer, Nigeria struggles with electricity provision, with over 57% of the population lacking grid access—particularly in rural areas. Off-grid solar PV systems offer a practical solution, capable of bypassing traditional grid expansion to deliver clean, affordable, and reliable electricity to remote communities. With solar PV prices having fallen by approximately 90% over the past decade, these systems are increasingly cost-effective and scalable.

Economic Determinants

High initial costs continue to be a major obstacle to solar energy adoption in Nigeria (Oladipo et al., 2023). Although operating costs for solar systems are relatively low, the upfront expenses— particularly for quality photovoltaic (PV) panels, batteries, and inverters—can be prohibitive for SMEs with limited access to financing (Akanbi & Fowowe, 2021). However, innovative financing approaches such as pay-as-you-go solar models and micro-lending programs have demonstrated increased adoption rates among SMEs in East Africa (Mutua et al., 2022), indicating potential applicability in Nigeria.

Technical Determinants

The reliability of solar systems and the availability of maintenance services are critical factors influencing adoption. A shortage of local technical expertise can discourage SMEs from investing in solar energy (Yusuf & Danladi, 2019). SMEs require assurance of consistent power supply, minimal downtime, and accessible repair services (Adeleke et al., 2021). Studies in Ghana indicate that SMEs are more likely to adopt solar technology when suppliers offer after-sales support and warranties (Mensah et al., 2020).

Policy and Institutional Determinants

Government policies, tax incentives, and exemptions on import duties for solar equipment play a significant role in driving adoption (Okafor et al., 2022). Nigeria's National Renewable Energy and Energy Efficiency Policy (NREEEP) seeks to increase the share of renewable energy, but challenges in implementation remain (IEA, 2023). In other countries, such as India, mechanisms like feed-in tariffs and net metering have accelerated solar adoption among SMEs (Kumar & Singh, 2021).

Socio-Cultural Determinants

Perception and awareness also affect adoption. Many SMEs remain hesitant to invest in solar energy due to limited information or prior experiences with low-quality products (Umeh & Eze, 2020). Educational campaigns and demonstration projects have been shown to build trust and increase adoption rates (Oyebanji et al., 2023).

Renewable Energy Adoption in Developing Countries

As Martinot (2002) noted, rising energy demand driven by population growth and improved living standards has increased recognition of the need for clean and modern energy alternatives. Renewable energy technologies, particularly in rural and remote areas, offer a promising solution to expand energy access. The Renewable Energy Association (REA, 2009) defines “Renewable Energy Technology” as systems that harness energy sources without depleting or harming natural resources. Sustainable sources such as solar and wind can meet energy demands while minimizing environmental impact.

Research highlights the significant benefits of off-grid renewable energy systems across economic, social, and environmental dimensions. Economically, these systems are cost-effective over the long term, with lower maintenance requirements compared to conventional energy solutions, and they can generate surplus energy for productive uses, increasing user income.

Socially, renewable energy reduces time spent on household tasks like fuel collection, improves health outcomes by decreasing exposure to indoor air pollution, and enables educational and social activities. Environmentally, solar energy contributes to climate change mitigation by replacing fossil fuel consumption, reducing CO_2 emissions, and supporting sustainable energy development.

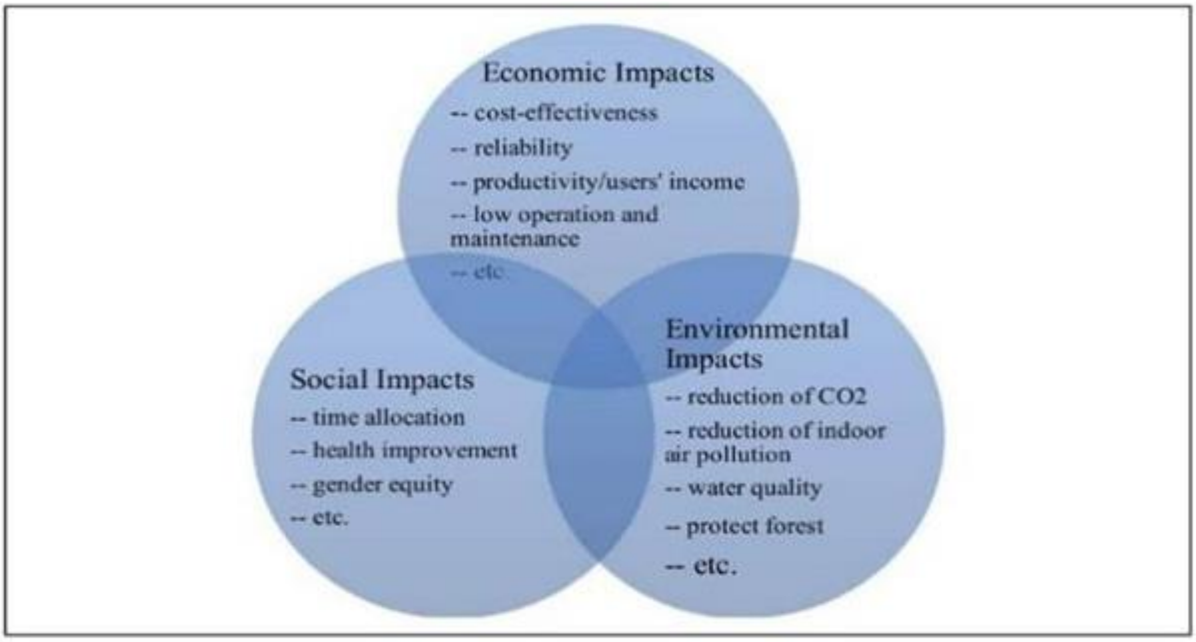

Figure 2: Renewable Energy Impacts on Rural Sustainable Development.

Samuel et al. (2021) investigated the socio-economic impacts of off-grid energy access systems in rural southwest Nigeria, focusing on Gbamu village. Their study examined how a solar hybrid mini-grid supports local entrepreneurship. Findings revealed that access to reliable and affordable energy significantly increased business activity, employment, and household incomes while reducing reliance on petrol and diesel generators, thereby lowering carbon emissions and mitigating air pollution-related health risks. Using regression analysis, the study identified factors influencing business income generation, concluding that dependable energy access is crucial for rural socio-economic development. The mini-grid not only supported existing businesses but also attracted new ventures, such as Nigeria's first commercial electric motorcycles, fostering economic growth and environmental sustainability. This research contributes to the broader understanding of how electricity access can transform rural economies and highlights the potential of off-grid solutions in addressing energy poverty.

Oladeji et al. (2022) explored the challenges and solutions for providing clean, reliable electricity to remote rural areas. The study reviewed Nigerian government initiatives, policies, and agencies, including the Nigeria Electrification Project (NEP) and the Rural Electrification Agency (REA), aimed at expanding rural energy access. It detailed ongoing collaborations with the World Bank and African Development Bank to implement solar mini-grids and other off-grid projects. The research identified off-grid locations and assessed their renewable energy potential, proposing a community-driven business framework to ensure sustainable electrification. The study concluded that deploying mini-grids is more feasible and cost-effective than extending the national grid to remote communities, given the high costs and environmental impacts of traditional grid expansion. Mini-grid solutions, incorporating various renewable energy sources, offer benefits such as affordability, lower maintenance, reduced transmission losses, and fewer regulatory barriers. Local enterprise involvement was emphasized to improve the reach and sustainability of rural electrification efforts.

The authors introduced the Mini-grid Value Chain for effective project implementation and proposed an Improved Local Electrification Committee (ILEC) Model to enhance affordability and sustainability. Unlike the Village Electrification Committee (VEC) model, ILEC integrates expert contractors for technical operations and maintenance while training local technicians for preventive maintenance. The model encourages community participation in project management, grievance resolution, and coordination with the REA. A Local Energy Fund (LEF) managed by the community ensures emergency replacements and operational continuity, making ILEC potentially more effective than VEC due to its emphasis on technical expertise and community involvement.

Feron (2016) assessed rural electrification programs based on off-grid photovoltaic (PV) systems in developing countries, focusing on four sustainability dimensions: institutional, economic, environmental, and socio-cultural. The study highlighted barriers such as weak institutions, poor regulations, incomplete decentralization, and lack of adaptability. Economic sustainability was examined in terms of funding, affordability, cost-effectiveness, and reliability, emphasizing the need for subsidies and complementary infrastructure like training. Environmental sustainability concerns included insufficient awareness, regulations, and incentives, which could lead to negative impacts from clean technologies. Socio-cultural barriers, such as the need for social acceptance, cultural equity, and proper technology implementation, were also noted. The review concluded that off-grid PV sustainability is often compromised by these multidimensional challenges, and stakeholders must address them to improve rural electrification outcomes.

Kehinde et al. (2023) conducted a technical and economic feasibility study of an optimal hybrid renewable energy system (HRES) for rural electrification in Edem Urua, a remote village in southern Nigeria. Using mathematical modeling and the HOMER Pro Microgrid Analysis Tool, they designed and sized system components, including solar, wind, diesel generators, and battery storage. Three optimal configurations were identified: Solar PV/Diesel/Battery (SDB), Solar PV/Wind/Diesel/Battery (SWDB), and Solar PV/Wind/Battery (SWB). The SDB system had a net present cost (NPC) of $233,867.86, a cost of energy (COE) of $0.062/kWh, renewable penetration fraction (RPF) of 95.219%, and CO_2 emissions of 8,231 kg/yr. The SWDB system had an NPC of $227,082, COE of $0.063/kWh, RPF of 97.34%, and CO_2 emissions of 4,621 kg/yr. The SWB system achieved 100% renewable penetration with zero CO_2 emissions, an NPC of $264,046.10, and a COE of $0.073/kWh. These results align with the **UNFCCC "**Race to Zero" campaign to reduce global CO_2 emissions by 45% by 2030 and reach net-zero by 2050. The study concluded that these HRES configurations are both technically feasible and economically viable for rural electrification, with substantial potential to reduce emissions and contribute to global climate action goals.

However, Oluwarotimi Delano Thierry In (Odou, 2020**)** conducted a review on the techno-economic feasibility of a hybrid renewable energy system (HRES) for sustainable rural electrification in Benin, using the village of Fouay as a case study. The study evaluated an HRES combining solar photovoltaics (PV), diesel generators (DG), and battery storage.

Optimization, simulation, and sensitivity analyses were carried out using HOMER software. Results indicated that the PV/DG/battery configuration was the most cost-effective system, with a cost of energy (COE) of $0.207/kWh. However, Olatomiwa, Mekhilef and Huda (2016) carried out an economic assessment of hybrid energy systems for rural electrification across Nigeria's six geo-political zones. The study analyzed the feasibility of various power generation configurations, including solar arrays, wind turbines, and diesel generators, using HOMER software. They assessed net present costs, COE, and renewable penetration fractions, concluding that the PV/diesel/battery hybrid system was the most economically viable option. The study also highlighted the potential for significant reductions in fuel consumption and CO_2 emissions, emphasizing that government subsidies and tariff incentives are necessary to encourage renewable energy investment, alleviate poverty, and promote sustainable rural electrification.

Diemuodeke et al. (2016) explored the penetration of solar photovoltaic (PV) systems in Nigeria and noted that despite high solar resource potential, distributed PV adoption remains low. The study indicated a gap between government policy targets and actual implementation. Data on solar potential across Nigeria's six geo-political zones revealed a range of 3.393–6.669 kWh/m²/day, with the northern zones exhibiting higher solar potential than the southern regions. The study compared the levelized cost of electricity (LCOE) of PV systems with diesel generators and kerosene lamps, finding PV systems to be more affordable for rural household lighting (LCOE: $0.387–$0.475/kWh). The authors stressed the need for fiscal and energy policies to create a market for PV systems, which could significantly improve rural electrification and climate change mitigation. Decentralized solar electrification was recommended as a viable solution to Nigeria's electricity access challenges.

The study highlighted the progress Nigeria has made in solar and mini-grid deployment, citing achievements by the Rural Electrification Agency (REA) and support from international bodies like the World Bank. Tools such as the Off-grid Mini-grid Explorer web map have helped identify priority areas for electrification projects. Government facilitation through policy alignment and enabling private investment is crucial for building a sustainable energy sector.

Overall, Nigeria's advancements in the solar and mini-grid sector demonstrate the country's commitment to universal energy access. This model serves as an example for other countries facing similar challenges. The focus on clean energy solutions, such as solar mini-grids, not only supports environmental sustainability but also fosters local economic development and reduces dependence on fossil fuels. Continued government and international support will be essential to sustain momentum and achieve 2030 and beyond energy goals. Currently, Nigeria has 21 identified off- grid solar power systems across 11 states, with capacities ranging from 100–120 MW.

Studies on the Nigerian Context

The Nigerian power sector has faced persistent challenges over an extended period, largely due to historical corruption, which has hindered development. Research indicates that corruption has significantly constrained socio-economic growth over the past two decades (Sambo et al., 2012). Defined as the "abuse of entrusted power for private gain," corruption has undermined economic growth and created investment uncertainty within the power sector and across sub-Saharan Africa (Obuah, 2010). Furthermore, the gas-dominated nature of Nigeria's electricity grid has contributed to frequent power supply failures, often due to insufficient gas availability for grid plants (Gatugel et al., 2015). Poor maintenance has compounded these challenges, leaving much of the grid infrastructure outdated and non-functional (Alao & Awodele, 2018).

In response, the Nigerian government has implemented energy initiatives under the Power Sector Reform, aiming to address electricity shortages, improve efficiency, and diversify energy options (Imam, Jamasb, & Liorca, 2019). These reforms attempt to mitigate energy scarcity, enhance reliability, and encourage investment in the sector, addressing both historical and technical barriers to sustainable electrification.

Development of Solar PV in Nigeria

Natural conditions for solar energy exploitation, with average annual global horizontal irradiation ranging from 1,534 to 2,264 kWh/m² (Okoro & Madueme, 2018). Despite this potential, over 65 million rural residents remain without access to electricity (World Bank, 2020). Although the country's installed generation capacity ranges between 12–13 GW, frequent power outages, grid collapses, sabotage, and vandalism have necessitated reliance on backup diesel generators of equivalent capacity (IEA, 2019).

To tackle these challenges and reduce carbon emissions, Nigeria's 2022 Energy Transition Plan sets ambitious targets to deploy substantial solar PV capacity, aiming for 197 GW by

2050 and 250 GW by 2060 (Federal Republic of Nigeria, 2022). The plan includes interim goals for 2030, focusing on centralized PV production, solar mini-grids, solar home systems, and hybrid solar-battery solutions. Despite these plans, Nigeria lags behind African nations such as Kenya, Morocco, South Africa, Uganda, Senegal, and Rwanda in renewable energy adoption. Compared to countries like the United States, Germany, Denmark, Japan, South Korea, and the United Kingdom, Nigeria struggles to advance solar energy technologies effectively (Ozoegwu, Mgbememe, & Ozor, 2017).

A lack of robust local innovation and research and development has been identified as a major constraint. A 1999 survey by the Energy Commission of Nigeria reported 43–50 solar companies and research centers involved in PV system installation and maintenance. However, only a few of these companies are engaged in battery production for PV systems, highlighting the need to strengthen local capacity in solar technology development and support.

The Nigerian power sector has faced persistent challenges, many stemming from historical corruption, which has hindered its development. Corruption has been identified as a major barrier to socio-economic progress over the past two decades (Sambo et al., 2012). Defined as the "abuse of entrusted power for private gain," corruption has adversely affected economic growth, particularly within the power sector, creating an environment of investment uncertainty across Nigeria and sub-Saharan Africa (Obuah, 2010).

Moreover, the country's reliance on a gas-dominated grid has contributed to frequent power supply failures, often caused by insufficient gas availability for grid plants (Gatugel et al., 2015). Poor maintenance practices have further compounded these issues, leaving much of the grid infrastructure outdated and non-functional (Alao & Awodele, 2018). Nevertheless, several studies highlight financing and policy gaps as major barriers to solar adoption:

1. Adebayo (2021) found that high capital costs deter small firms in Lagos.
2. Okafor and Obinna (2022) observed that firms with access to credit facilities were three times more likely to adopt solar systems.
3. Musa et al. (2023) revealed that government incentive awareness significantly increases adoption probability among SMEs in Abuja.
4. In Ghana, Amponsah and Mensah (2020) used a logistic model and found that reliability perceptions and firm size were critical predictors of adoption.

Empirical/research Gaps

While prior studies explored renewable adoption broadly, few have integrated firm, economic, institutional and technical dimensions using a mixed-method and multivariate modeling approach focused on North-Central Nigeria. Furthermore, most studies focused on household or large-scale industrial contexts (Adeleke et al., 2021; Oladipo et al., 2023). Few have examined SMEs in the North Central region, which have distinct operational and financial realities. Moreover, there is limited integration of socio-cultural variables with economic and policy determinants in existing models, creating a gap this study intends to address

Methodology Research Design

A mixed-methods descriptive and correlational survey design was adopted to capture both quantitative and qualitative insights.

Population and Sample

The population comprised SMEs in manufacturing, services, and agro-processing sectors across six North-Central states. A stratified random sample of 900 SMEs was selected, alongside 200 key stakeholders (solar vendors, financial institutions, and government energy officers).

Data Collection

Two structured questionnaires and an interview guide were used:

1. **SME Questionnaire:** Captured firm attributes, cost perceptions, financing access, awareness, and technical perceptions.
2. **Stakeholder Interview Guide:** Gathered qualitative insights on policy implementation and market dynamics.

Analytical Techniques

Quantitative data were analyzed using:

1. **Logistic Regression:** Determinants of adoption (binary: adopter vs. non-adopter).
2. **Ordered Probit Model:** Levels of adoption (partial, moderate, full).
3. **Chi-Square Tests:** Associations between categorical variables (sector and adoption).
4. **OLS Regression:** Effect of determinants on solar investment levels. Qualitative responses were coded thematically to complement quantitative results.

Results and Analysis Descriptive Statistics

Variable	Mean	SD	Min	Max
Firm Size (Employees)	36.4	18.2	5	210
Solar Installation Cost (₦m)	1.85	0.77	0.4	4.5
Awareness Index	0.62	0.19	0.2	1.0
Reliability Perception	0.71	0.15	0.3	1.0
Adoption Status (1=Yes)	0.58	0.49	0	1

Source: Field work (2025)

Distribution of Solar Adoption among SMEs

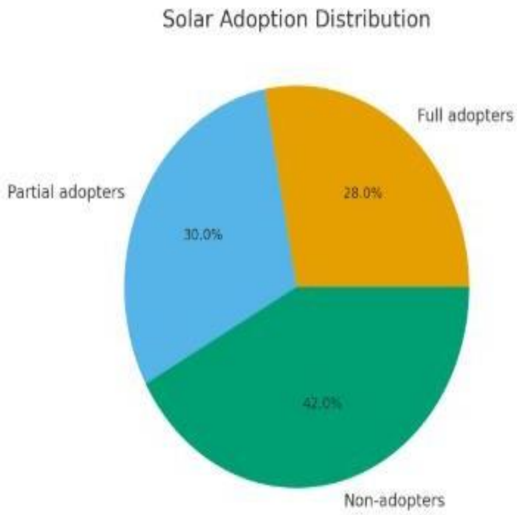

Figure 3: Solar Adoption Distribution. (Pie Chart)

(Pie chart visually depicts the adoption share across the 900 SMEs.)

Sectoral Distribution of Adopters

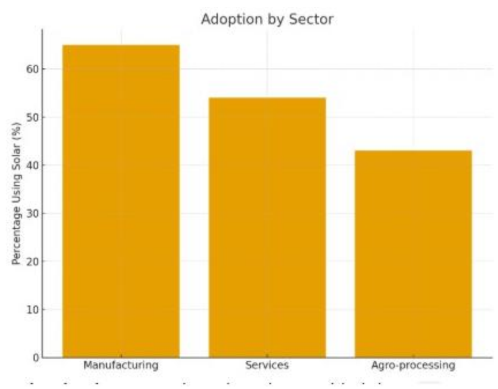

Figure 4: Bar Chart – Adoption by Sector

Sector	% Using Solar
Manufacturing	65%
Services	54%
Agro-processing	43%

Source: Field work (2025)

The manufacturing sector shows higher adoption due to higher power intensity and operational need.

Logistic Regression Results

Variable	Coefficient	Std. Error	z	p- value	Interpretation
Firm Size	0.214	0.051	4.19	0.000	Larger firms more likely to adopt
Installation Cost	-0.472	0.102	- 4.63	0.000	Cost reduces adoption
Financing Access	0.308	0.074	4.16	0.000	Increases adoption likelihood
Awareness of Incentives	0.256	0.081	3.16	0.002	Positively influences uptake
Reliability Perception	0.423	0.117	3.61	0.000	Significant driver
Maintenance Accessibility	0.192	0.091	2.11	0.035	Positive effect

Source: Field work (2025) Model Summary:

1. LR χ^2 (6) = 184.32, $p < 0.001$
2. Pseudo $R^2 = 0.42$
3. Correctly classified = 78.4%

Ordered Probit Model (Adoption Levels)

Higher awareness, financing support, and firm size significantly influence movement from partial to full adoption ($p < 0.01$).

OLS Regression (Solar Investment Intensity)

Dependent Variable: Amount invested in solar (₦ million)

Predictor	β	t	Sig.
Firm Size	0.39	5.11	0.000
Cost Perception	-0.42	-4.76	0.000

Regulatory Clarity	0.24	2.87	0.004
Reliability	0.37	4.62	0.000

Source: Field work (2025)

Adjusted $R^2 = 0.47$, $F(4,895) = 38.21$, $p < 0.001$

Chi-Square Analysis

A significant association exists between sector type and adoption status ($\chi^2 = 26.44$, $p < 0.001$), indicating that sectoral energy intensity influences decision-making.

Graphical Interpretation

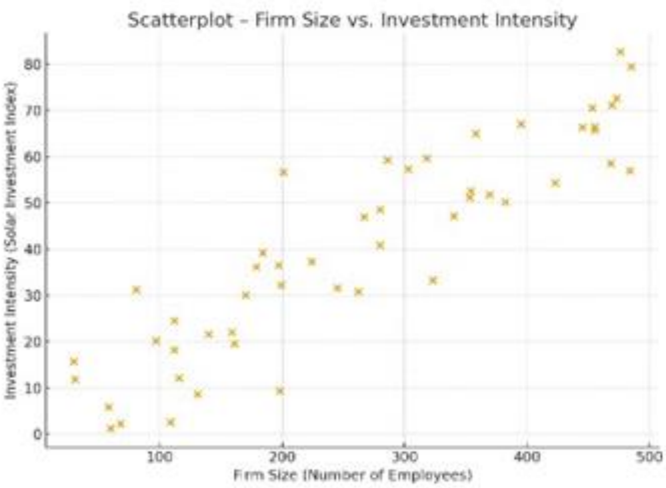

Figure 5: Scatterplot – Firm Size vs. Investment Intensity

A positive upward trend indicates that larger SMEs invest more in solar systems.

DISCUSSION

Findings confirm that firm characteristics, cost and financing access are primary determinants of solar energy adoption, consistent with previous studies (Okafor & Obinna, 2022; Musa et al., 2023). The significance of awareness of incentives underscores the importance of effective communication between government and SMEs. Technical perceptions, particularly reliability and maintenance accessibility, further shape adoption behavior, aligning with Rogers' diffusion theory.

CONCLUSION AND RECOMMENDATIONS CONCLUSION

This study demonstrates that solar energy utilization among SMEs in North-Central Nigeria is significantly driven by firm size, economic feasibility, institutional awareness and technical reliability. High installation cost and limited financing options remain key obstacles.

RECOMMENDATIONS

1. **Policy Incentives:** Strengthen dissemination of existing solar tax credits and subsidy programs.
2. **Financing Models:** Promote accessible credit schemes through partnerships between financial institutions and renewable vendors.
3. **Technical Support:** Establish regional maintenance hubs for solar system support.
4. **Awareness Campaigns:** Expand information outreach through business associations.
5. **Regulatory Clarity:** Streamline licensing and import regulations for solar equipment.

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