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SPATIAL DISTRIBUTION PATTERN OF OFF-GRID SOLAR ENERGY INTERVENTION IN THE FEDERAL CAPITAL TERRITORY

ADAMU MOHAMMED A.; SANGARI D. U.; KPALO SUNDAY Y.; & BELLO INNOCENT E.

Department of Geography, Nasarawa State University, Keffi Nigeria

Corresponding Author: ardoa4@yahoo.com

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ABSTRACT

The spatial distribution pattern of off-grid solar energy interventions in the Federal Capital Territory (FCT), Nigeria, reflects critical dynamics in the pursuit of energy access and sustainable development. This study investigates the geographic allocation, concentration and socioeconomic impacts of off-grid solar intervention, including solar mini-grid, solar home system, solar lanterns and street lighting, across the six Area Councils of the FCT. Using a

INTRODUCTION

Renewable energy is an energy source that is replenished by natural processes at a rate that equals or exceeds its rate of use (Widén et al., 2015). Such renewable energy sources are solar energy, wind, geothermal, biomass, and hydropower sources, which have found significant application in providing modern energy for many underreached areas in Africa (Ang et al., 2022). Among the renewable sources, solar energy is one of the most preferred. This is due to solar energy technologies providing clean and sustainable energy and being environmentally friendly, i.e., it reduces carbon emissions, which mitigates climate change. Also, the energy source is cost-effective and easily deployed to underserved areas and households (Bogdanov et al., 2021). About 11,556 MW of solar photovoltaic has been the continent's main source of renewable electricity, which made

combination of geospatial analysis, that is, a non-parametric approach using the Kernel Density Estimation (KDE). Also, solar energy data was collected through a questionnaire from about 335 respondents who are users of solar energy interventions across the FCT. The research identifies spatial disparities and clustering tendencies in the deployment of solar energy infrastructure. The findings revealed that while some urban and peri-urban areas benefit from significant solar interventions, many rural communities remain underserved, highlighting gaps in planning and the socio-economic strength of the region. The outcomes showed that i) more solar energy users were identified in the AMAC region and the lowest in Kuje AC; ii) solar energy interventions were significantly clustered among energy users at statistical significant value (p-value) of 0.01 and which implies that solar energy interventions were representative and have met their energy demand; iii) most of the Area Councils received an average of about 11 – 15 hours of solar electricity indicating a high levels of socio-economic benefits; iv) the AMAC region claimed to experience more socio-economic benefits among other Area Councils. The study underscores the need for a more inclusive and data-driven approach to solar energy interventions to ensure equitable access and alignment with national electrification goals.

Keywords: Off-Grid Solar Energy Intervention, Federal Capital Territory, Spatial Distribution, diffusion, Kernel Density Estimate

it the most preferred renewable energy source in the region (Pourasl et al., 2023). Between 2011 and 2020, about 25 GW of renewable energy was generated in Africa as against 242 GW forecasted to be generated between 2021 and 2030. This increase in renewable energy capacity is a result of a drastic reduction of about 52% in the price of solar photovoltaic (PV) by 2030 (IEA, 2022).

In Sub-Saharan Africa, solar PV plays an important role in providing modern energy to several rural, peri-urban and urban areas to supplement either the unreliable supply of electricity in the urban areas or the underserved rural regions (Quansah et al., 2016). Many countries in the region have embraced clean technology and harnessed its social and economic benefits to support their low-carbon development and clean energy initiatives (Wanjiku, 2024). For instance, several countries in the region, such as Ghana, Senegal, the Ivory Coast, and Nigeria, have embraced clean technology to provide reliable electricity to homes, bolster small and medium-scale enterprises and ensure the overall well-being of their citizens (Adewuyi et al., 2020). Solar PV has been deployed to sensitive sectors such as the health, security, agriculture, and education sectors to ameliorate the already exacerbated energy deficit. Although many regions in SSA have significant solar energy resources, 600 million people are without access to reliable electricity in Africa and are yet to meet their energy needs in the most sensitive sectors.

Nigeria, the largest black nation (with over 210 million people) in the world, is also referred to as the world energy poverty headquarters, where over 85 million people, representing 4 out of 10 people without access to electricity (World Bank, 2024). Yet, the country struggles to meet its basic energy demand despite having significant solar energy resources and being Africa’s largest economy. In addressing the epileptic power supply and providing modern energy to the underserved region of the country, Nigeria's power sector, through the Rural Electrification Agency (REA), has made deliberate action and significant investment in addressing the menace of modern energy. Although several successes were recorded in providing electricity to many rural areas, Ministries, Departments and Agencies (MDAs) and institutions in the country through at the state level and local government still use unsustainable traditional biomass to provide electricity in their household, schools and primary health centers, among others (Odunjo & Omolola, 2013; Okafor et al., 2022).

Having identified the energy gap in Nigeria's power sector, several studies have provided significant contributions to addressing the challenges of unstable modern energy in Nigeria. A few included a System Dynamics modelling paradigm to explore possible developmental scenarios that present different sustainable pathways to address the country’s power challenges (Shari, 2018; Golobish et al., 2022; Shari et al., 2020, 2024) including clean cooking (B. E. Shari et al., 2022). Including scholarly research (Dioha, 2018, 2020; Dioha & Emodi, 2019; Dioha & Kumar, 2020). Although the studies have made a very relevant argument on how to address the energy bottlenecks in Nigeria across several sectors, including the residential, commercial and planning of the country’s net-zero energy transition (B. E. Shari et al., 2024). However, currently, there is limited understanding of how to address the energy situation in the country’s Federal Capital Territory, Abuja. On this note, the study presents a relevant argument that the FCT could become self-sufficient in modern energy by assessing the spatial distribution of off-grid solar energy intervention in the Federal Capital Territory towards energy sustainability in the Mega City.

The Federal Capital Territory (FCT), Nigeria, also has a share of the unstable power supply due to the consistent national grid collapsing about 12 times in 2024 (Bassey, 2024). As a result, many urban dwellers opt for solar home systems, while those in rural areas depend on either mini-grids or solar lanterns, including solar street lighting on major roads

(Lemaire, 2018; Yadav et al., 2019). Despite the government and individual intervention to provide immediate succour to the unprecedented power insecurity, Nigeria still ranks low in the global energy index, including the FCT. Thus, the current study aims to investigate through a spatial distribution approach the off-grid solar energy Intervention in the Federal Capital Territory.

Study Area

The study area is the Federal Capital Territory (FCT), Abuja, Nigeria. It lies in the central part of Nigeria, as shown in Figure 3. The Federal Capital Territory (FCT) shown is the capital of Nigeria, located between the latitudes 8°30'0" N to 9°30'0"N and longitude 6°45'0"E to 7°45'0"E, placing it approximately in the center of Nigeria. It occupies an area of approximately 8000 Km^2. Also, according to the National Population Commission and the National Bureau of Statistics, the population of FCT was estimated at 3,564,126 in 2016 (NPC, 2006). Similarly, the macro trend estimated the population of Abuja to be about 3,840,000 at a growth rate of 5.15% in 2023. The population comprises the Gwari, Koro, Ganagana, Gwandara, Afo, and Bassa ethnic groups, predominantly dairy farmers.

The FCT is located north of the confluence of the Niger and Benue rivers. It is bordered by the states of Niger to the west and northwest, Kaduna to the northeast, Nasarawa to the east and south, and Kogi to the southwest. FCT is divided into six area councils, namely: Gwagwalada, Abaji, Kwali, Kuje, Bwari, and Abuja Municipal Area Councils (Opeyemi et al., 2022). The research area's location would consider many settlements (villages/towns and local government districts/headquarters) across the six central councils in the Federal Capital Territory.

Abuja lies at 1,180 feet (360 metres) above sea level and has a cooler climate and less humidity than is found in Lagos. The region is underlain by crystalline rocks consisting of granites and gneisses. Mineral resources include Cassiterite, Clay, Dolomite, Gold, Lead/Zinc, Marble and Tantalite (Atakpa, 2019; MFA, 2023) . The vegetation is mainly savanna with limited forest areas. Agriculture, the economic mainstay, produces yams, millet, corn (maize), sorghum, and beans

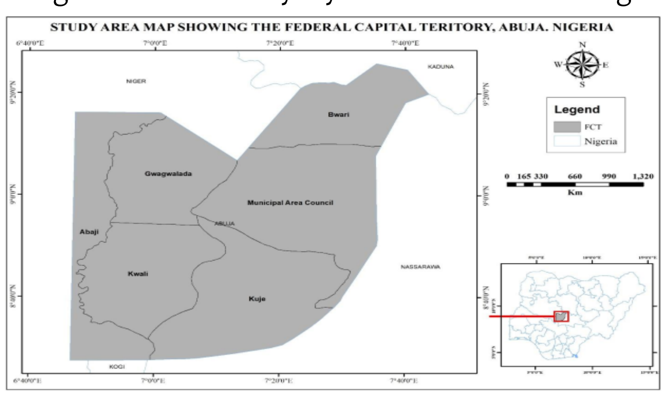

Figure 1: The study area, Federal Capital Territory, Nigeria
Source: (Opeyemi et al., 2022)

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Method

The study was conducted through a geospatial and statistical survey across the six Area Councils in the Federal Capital Territory. The Area Councils were stratified into urban, peri-urban and rural strata. To do this, primary data types were collected for the study investigation, which comprised households or residential, commercial, cultural and religious centers, and healthcare solar users. The survey was conducted based on respondents who identified using solar energy intervention to meet their basic energy needs. The users of solar energy technologies identified included solar home system (SHS), solar mini grid and solar lantern. Enumerator inspects the building or infrastructure that mounts solar panels on roof-tops or a support system, battery housing and basic solar system maintenance practices

The primary data collected through survey aimed at collecting solar energy intervention through a concise and well-articulated questionnaire administration to about 400 respondents. About 335 questionnaires were well attended to with completed information, the remaining 65 questionnaire were either not returned or returned with incomplete information. The questionnaire captured the social, economic and technical dimensions of solar energy interventions. Other thematic sections that would be considered include: a) demographic characteristics b) energy demand assessment c) economic and income assessment; d) cultural patterns; d) gender and family distributions; e) community and institutional structure; f) political and social resources; g) energy consumption and expenditure; and h) utilization rate of solar resources and technologies. More so, during the questionnaire administration, the geographically referenced with a Global Positioning System (GPS) were collected by recording the longitude and latitude points of each point where questionnaires were administered.

Ab initio, a reconnaissance field (RS) survey was conducted to gather intelligence about the Area Councils towards the primary data collection. The reconnaissance survey was used for the research design control and to enable a proper understanding of research materials and instruments of data collection. This approach enables to estimation of the study sample size from the ambiguous total population size (Tourangeau & Plewes, 2013). During the reconnaissance survey, a random and quick examination of the study area and research tools was done; the assessment was aimed at identifying key features, patterns, and potential areas of interest. More specifically, the reconnaissance survey was conducted to identify basic patterns and characteristics of solar energy intervention usage across three Area Councils, which included Abuja Municipal Area Council (AMAC), Gwagwalada and Bwari Area Councils. Also, the conduct of the RS helps test the survey

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tools (research questionnaires and interview guidelines) to weed out unnecessary questions and include variables that could have been overlooked.

Clustering and Spatial Heterogeneous Analysis

A clustering and spatial heterogeneous analysis was used to analyzed the geospatial data. According to the ESRI dictionary, spatial analysis is the process of examining the locations, attributes, and relationships of features in spatial data through overlay and other analytical techniques to address a question or gain useful knowledge and identify properties and patterns. Spatial analysis is also a statistical analysis based on patterns and underlying processes (Paramasivam & Venkatramanan, 2019; Bishop & Giardino, 2022).

The solar energy users in FCT show significant evidence of clustering. As such the spatial patterns as applied are to estimate how the intensity of solar energy users is spread across FCT. The point pattern, viz, intensity, was the cluster technique used in the study. The assumption of spatial heterogeneity was considered, which means that the intensity γ varies with location s in the geospatial location (Wang et al., 2004). This is illustrated in Equation 1, which γ_s is not a constant γ,

$$\gamma_s \neq \gamma \text{ for all s} \qquad 1$$

A non-parametric approach using the Kernel Density Estimation (KDE) was used as a weighted moving average of the data points (Węglarczyk, 2018). According to Equation 2, the KDE was implemented (Tjøstheim et al., 2022).

$$f(u) = \frac{1}{N_b} \sum_i K\left[\left(\frac{u-u_i}{b}\right)\right] \qquad 2$$

Where u is any location, K is the kernel function (a function based on distance), and b is the bandwidth, i.e., how far the moving average is computed with N_b as the number of observations within the bandwidth.

The study's clustering and spatial analysis were carried out based on Bishop & Giardino (2022) and the study made a succinct description of the spatial analysis of geospatial data. The method has been proven to have been applied across several case studies. A few of the case studies included the analysis of the spread of COVID-19 (Kang et al., 2022; Melin et al., 2020) and Spatial analysis of the factors impacting the spread of COVID-19 (Ahadnejad Reveshty et al., 2024). It has also been applied to investigate the distribution, patterns and relationships of health status (Li et al., 2024).

Result and Discussion

This section presents the spatial spread of solar energy projects across the six Area Councils of the FCT and also discusses the resulting outcome of the spatial analysis.

Table 1 shows the frequency distribution of data collection across the six Areas Councils in the FCT. The frequency and percentage presented in Table 1 are based on the distribution of the availability of solar energy technologies and intervention in the respective Area Councils.

According to Table 1, the AMAC, Gwagalada and Kwali Area Councils recorded the highest presence of solar energy intervention in that order, while Abaji, Bwari and Kuje Area Councils recorded, respectively, the lowest identified solar energy interventions either implemented by the government, private, public-private, or commercial sectors. Thus, a total of 335 solar energy users were interviewed and to obtain relevant solar energy information about their experience on the use of the technology. However, in this study, the spatial distribution of solar energy users is considered and investigated.

Table 1. Frequency Table of Respondents Council Area.

Region (Council Area)	Frequency	percentage
Abaji	33	9.85
Bwari	43	12.84
Gwagalada	66	19.70
Abuja Municipal (AMAC)	96	28.66
Kwali	50	14.93
Kuje	47	14.03
	335	**100**

The outcome of the frequency table provided a succinct illustration and distribution of solar energy users in the FCT. The illustration of the spatial distribution is presented according to the following i. Spatial Distribution of Off-grid Solar Interventions; ii) Clustered spatial pattern; iii) hours of solar electricity received; iv) socio-economic impacts and intervention performance.

Spatial distribution of solar energy intervention

Figures 2 and 3 present the spatial distribution of the solar energy intervention and the spread statistics, respectively, in the FCT. According to Figure 2, solar energy interventions were clustered across where it has been applied. Also, it revealed that more intervention was established in the AMAC. In addition, some Area councils have overlapped with others; for instance, the Kuje Area Council is of significant proximity to the AMAC, and as such, some interventions in the Area Councils closest to AMAC were found to have overlapped with AMAC.

In addition, Figure 3 revealed that the solar energy interventions were significantly clustered among energy users. This implies that solar energy interventions were representative and have met their energy demand. The clustered nature of Figure 2 can also be attributed to the fact that people live together in a particular location where the solar intervention is installed especially according to solar mini-grids.

Also, the outcome from the Figure 3 perspective implies the following: a significant value (p-value) of 0.01 implies that the distribution is statistically significant and the observation data from which the distribution was drawn provides strong evidence against the fact that solar energy interventions may not have met consumers' energy needs. Thus, the alternate hypothesis is accepted.

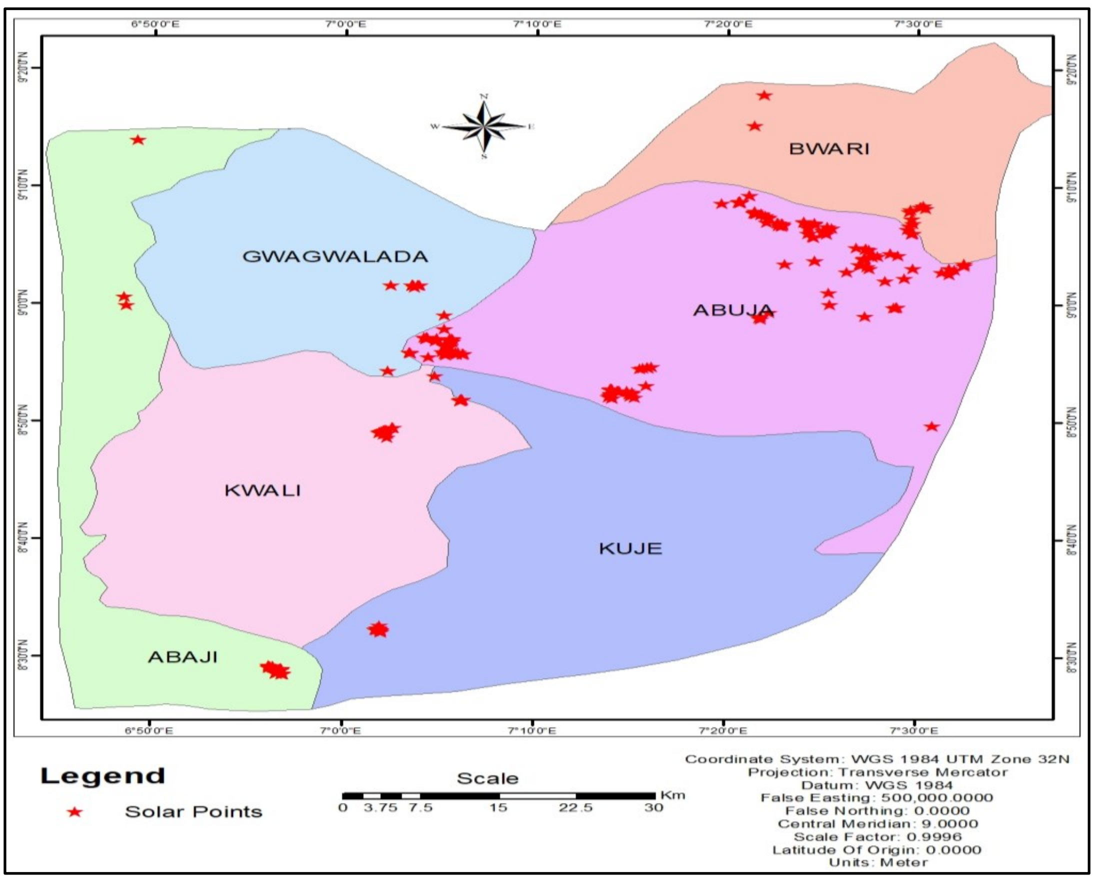

Figure 1. Spatial Distribution of Off-grid Solar Interventions in the Six (6) Area Councils in the FCT, Nigeria. Source: (Authors Field Survey, 2024)

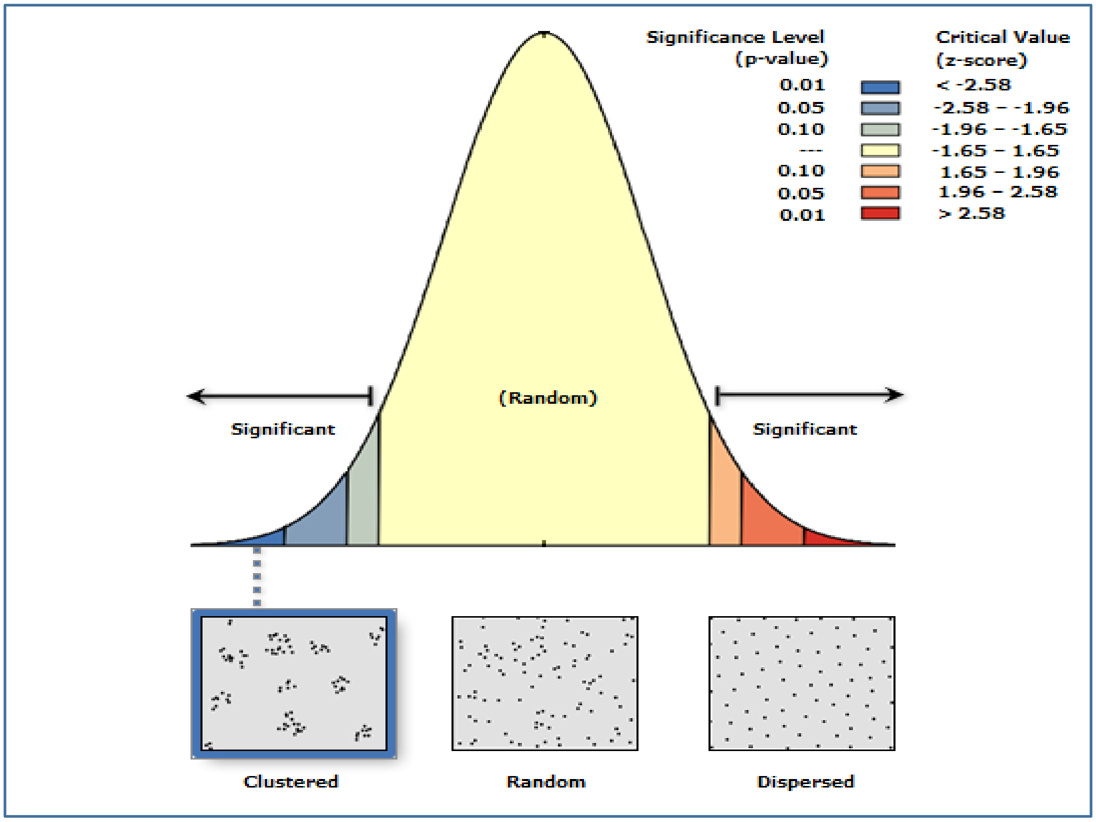

Figure 2. Clustered spatial pattern of the Solar point in the six Area councils in FCT, Nigeria. Source: (Authors' Field Survey, 2024).

In addition to assessing the spatial distribution pattern of off-grid solar energy intervention, Figures 4 and 5 are presented. Figure 4 shows the amount of solar energy/electricity received daily from the solar intervention. According to the spatial distribution pattern shown in Figure 4, most of the Area Councils received an average of about 11 – 15 hours of solar electricity. All of the solar energy users across the Area Councils claimed that their solar energy intervention provided them with an average of about 11 to 15 hours of solar electricity. However, some Area Councils also claimed they received an average of about 21 to 24 hours of electricity every day from their solar intervention.

In addition, the socioeconomic impact and performance of solar energy intervention were conducted and shown in Figure 5. According to Figure 5, many of the respondents experienced high levels of socio-economic benefits from the adoption and use of solar energy. However, most of the respondents in the AMAC Area Councils have claimed to experience high socio-economic benefits from the use of solar energy intervention.

Juxtaposing Figures 4 and 5 revealed that a correlation exists between the hours of solar energy received and corresponding socio-economic benefits. This claim is evident in the

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AMAC Area Council, where significant respondents claimed that they receive solar electricity for 11 -15 hours and the same Area Council claimed to experience more socio-economic benefits among other Area Councils.

Accordingly, the results from the study have revealed some crucial and relevant aspects of solar energy interventions across the six area councils in the FCT. Among the results obtained is the clustered nature of solar energy interventions, which supports international best practices of a decentralized energy system (Stritzke & Jain, 2021; Zalengera et al., 2020).

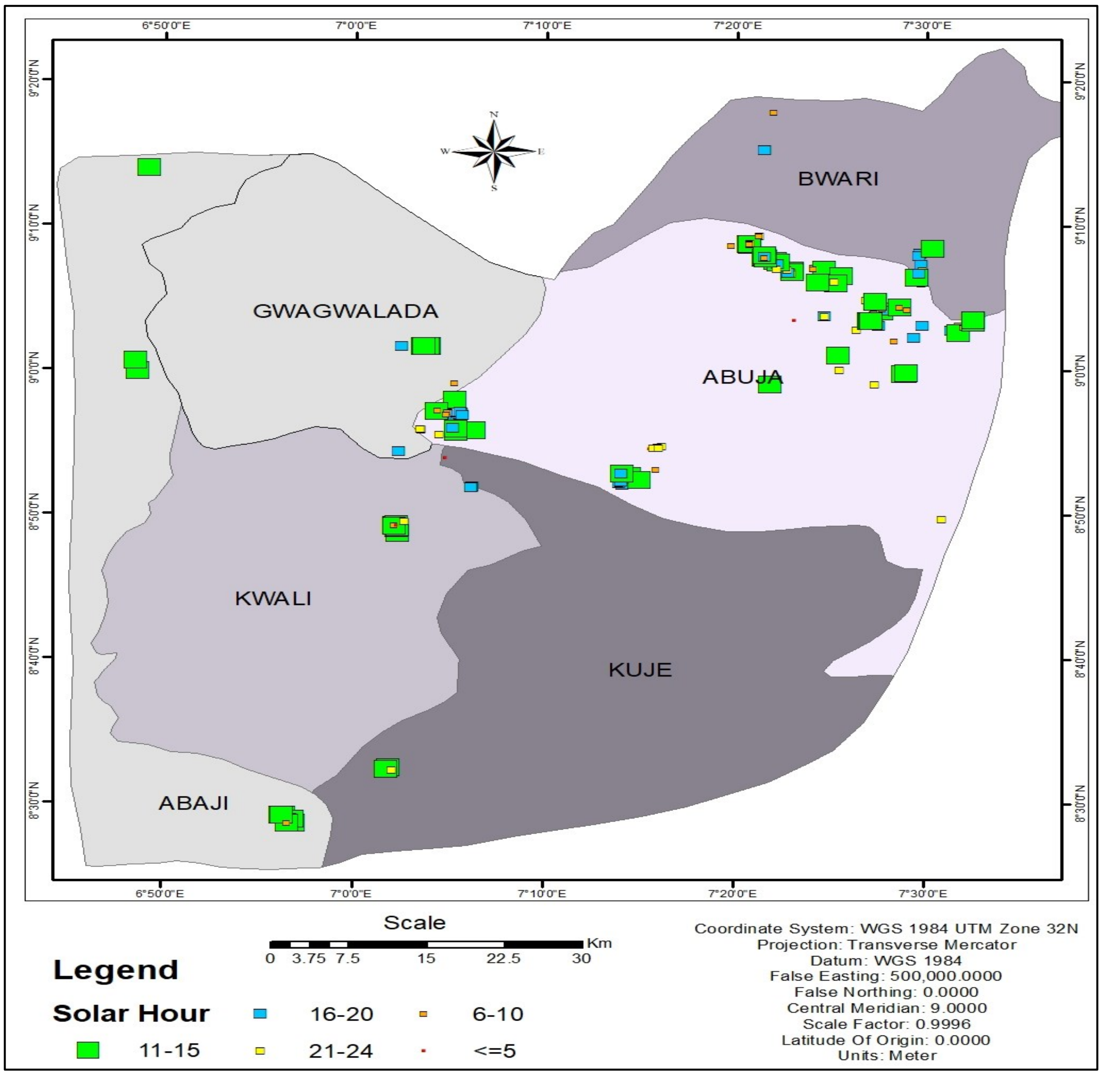

Figure 4. Hours of electricity received/generated from the solar project/intervention per day.

Source: (Authors' Field Survey, 2024)

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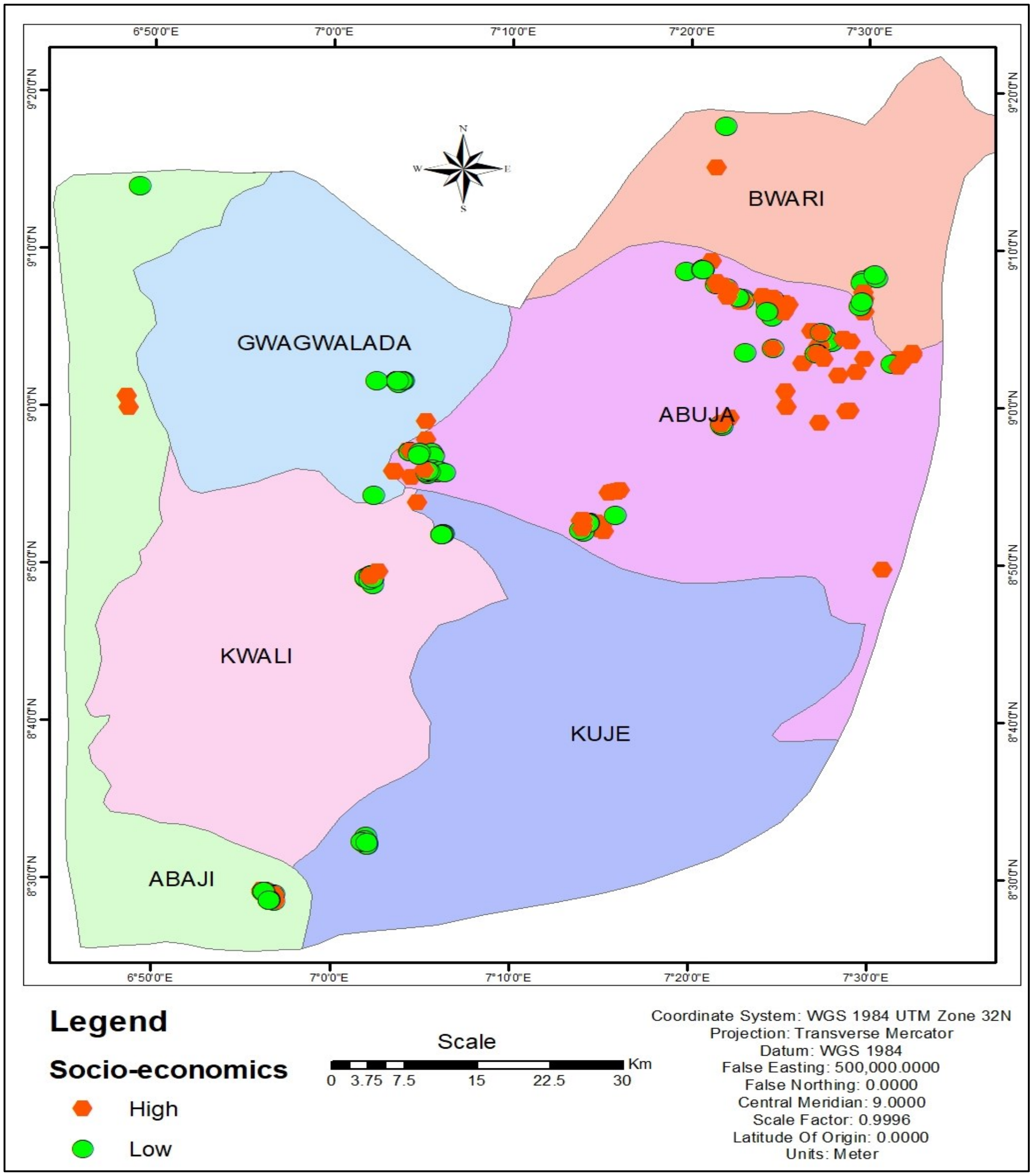

Figure 3. Socio-economic impact and performance of solar intervention
Source: (Authors' Field Survey, 2024)

Discussion

Our study has generated new insights and presented reliable narratives of solar energy interventions on how and where they could have the best impact, thus bridging the research gap and providing desired research findings to understand solar energy interventions. The study established that a holistic collaboration of the public and private sectors will provide a sustainable partnership for relevant stakeholders to be involved in solar energy across all sectors. The collaboration provided better clarity on the stakeholders' role, presenting and making feasible, reliable solar energy market strategies. The outcome from the stakeholder, the organization and their roles supports evidence from (Edomah et al., 2021; B. E. Shari et al., 2023) that a holistic stakeholder collaboration in the energy sector will not only provide clarity but also ensure sustainable energy access, especially in Nigeria. The outcome from the study also supports claims from McEwan (2017) which claim that solar energy distribution provides a novel paradigm of political and economic actors to enhance commercial power through establishing zones of socioeconomic development. It will also support social practices that enable the easy adoption of clean energy solutions and curb the energy access challenge (Ockwell et al., 2018).

Additionally, understanding how solar energy technologies are deployed could enable their planning, especially in regions with dense and scattered populations. The outcome from our study revealed the geospatial spread of solar energy intervention as clustered, which implies that solar energy interventions are implemented in areas with similar energy needs and with a common socioeconomic landscape. Thus, supports planning a sustainable clean energy system for areas connected and not connected to the national utility; hence, McEwan (2017) claimed that this could enable new territories to deploy forms of spatial and political-administrative exceptionality, and as an enabler for social development in many sub-Saharan African Countries (Casati et al., 2023).

Conclusion and Recommendation

The study investigated the geospatial attributes and spread of solar energy interventions in the FCT based on major off-grid technologies. The off-grid technologies considered were mini-grid, solar home systems and solar lanterns. The result was categorized according to the following criteria i) spatial distribution of solar energy interventions; ii) clustering analysis of the spatial pattern of the interventions and iii) the socioeconomic impact of the interventions. The spatial distribution of solar energy intervention revealed that the AMAC region received the most solar energy interventions in terms of solar home systems; however, other Area Councils were shown to have overlapped. Also, the cluster analysis indicated that solar energy interventions have heterogeneous attributes, such that the interventions are close together at a significant level (p-value) of 0.01. More so, notable socioeconomic impacts were identified and experienced among users of solar energy interventions in the Abuja Municipal Area Council (AMAC).

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Having established solar energy interventions in the FCT, the following recommendations are proposed.

- Appropriate need assessment study: there is a necessity for a reliable need assessment by the relevant intervention body, whether it be an individual, government, private entity, or non-governmental organization, to accurately investigate the energy requirements and current and projected energy needs of households, services, communities, or organizations. Hence, a need for auditing before the implementation of any solar energy intervention across the FCT. Such an assessment would enable the realization of socioeconomic benefits where solar interventions are initiated.
- Solar interventions work best with a distributed energy system: the study has identified, through a clustered and heterogeneously spread solar energy intervention, that the most suitable and dependable application of solar energy is via a distributed energy system. This suggests that solar interventions should be considered for diverse areas within the area councils—specifically, those with similar income levels, socio-cultural identities, and relatively clustered settlements.
- Need for improved energy efficiency: The study revealed that an average of 11-15 hours of solar electricity supply was available to consumers; this ratio could be significantly enhanced through appropriate energy efficiency measures. Therefore, energy efficiency technologies and conservation behaviours should be prioritized among end users of solar interventions.
- donor agencies involved in solar energy projects should ensure the productive use of energy by supporting initiatives that empower women and youth, as well as fostering agribusiness and other small- and medium-scale enterprises.

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