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Suitability and Socio-Economic Analysis of Hybrid Renewable Energy Systems Deployment in Rural Areas of Abuja, Nigeria

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Abstract: Access to sustainable and reliable electricity remains a pressing challenge in rural areas of Abuja, Nigeria, where grid extension is economically unviable and energy poverty persists. Hybrid Renewable Energy Systems (HRES), combining multiple renewable sources such as solar and wind with backup systems like biogas generators or batteries, have emerged as a viable solution to bridge this gap. This study conducts a geospatial suitability analysis to identify optimal locations for deploying HRES in rural communities of Abuja using Geographic Information Systems (GIS). By integrating environmental, topographic, and socio-economic criteria such as solar irradiance, wind speed, and land use, the study aims to guide stakeholders in prioritizing investment and planning. Data were sourced from satellite imagery, meteorological datasets, and national geographic databases, and analyzed using weighted overlay techniques suitability analysis in ArcGIS. This study successfully conducted a suitability analysis combining solar, wind, and biomass resource layers to identify Bwari (including Kurudu, Shere, Igu, and Kawu), Gwagwalada (Gawu), and Abuja Municipal Area Council (Karu, Orozo, Garki 1, and Nyanya) as the most promising locations for hybrid energy system deployment. The socio-economic analysis shows that energy access in rural FCT is limited, with 43.5% of respondents having limited access to electricity for 0-2 hours daily. Primary energy sources are traditional and polluting, with 35% using firewood, 32% relying on diesel generators, and 1.4% using solar energy. Most respondents are aware of renewable energy, with 86.4% believing it could benefit their community. Biomass resources, such as poultry waste and agricultural residues, are prevalent, with 91.2% willing to contribute financially.

Keywords: *Suitability Analysis, Mapping, Geographic Information Systems, Renewable Energy, Rural Communities, Abuja.*

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I. INTRODUCTION

Rural electrification constitutes a significant developmental challenge in Nigeria, particularly within the Federal Capital Territory (FCT), where rural areas in Abuja face persistent issues regarding access to reliable electricity. The International Energy Agency (2023) reports that over 40% of the rural population in Nigeria lacks electricity access, with this deficiency being especially acute in peri-urban and remote regions(IEA, 2023). The reliance on traditional biomass and kerosene for energy exacerbates health, environmental, and economic difficulties, thereby obstructing sustainable development. In response to both global and national commitments aimed at reducing carbon emissions and improving energy access, the implementation of Hybrid Renewable Energy Systems (HRES) presents a sustainable and economically viable alternative to traditional grid expansion, particularly in sparsely populated rural locales(Oghomwen Igbinovia & Igbinovia, 2018).

Hybrid systems typically combine various energy sources, including solar photovoltaic (PV), wind turbines, and occasionally small hydro or bioenergy systems, supplemented by batteries or diesel generators to ensure reliability(Solanke et al., 2024). Their modular design facilitates adaptability in addressing local energy demands while mitigating the drawbacks associated with single-source systems. However, the successful deployment of these systems necessitates comprehensive feasibility assessments that consider geographical, climatic, and socio-economic variables. Consequently, Geographic Information Systems (GIS) and spatial analysis methodologies have become

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essential for evaluating the appropriateness of locations for HRES implementation, allowing for the integration and analysis of diverse datasets to inform strategic planning (Lee et al., 2023).

This study investigates the spatial suitability for HRES deployment in the rural regions of Abuja, Nigeria, utilizing GIS-based multi-criteria decision-making techniques. As the capital of Nigeria, Abuja presents a distinctive scenario where urban development coexists with underdeveloped rural communities, particularly in area councils such as Abaji, Kuje, and Kwali. These regions are characterized by extensive land areas, low population densities, and favorable solar radiation conditions, rendering them suitable candidates for decentralized renewable energy systems(Lee et al., 2023). The objectives of this research are threefold: first, to identify the critical locational factors influencing HRES deployment; second, to develop a GIS-based model for site suitability analysis; and third, to produce suitability maps and policy recommendations to assist energy planners and investors(B. Oyinna et al., 2023). By concentrating on the rural communities of Abuja, this research contributes to the expanding body of literature on renewable energy planning in sub-Saharan Africa and illustrates the application of geospatial technologies in energy access initiatives. Furthermore, it aligns with Nigeria’s National Renewable Energy and Energy Efficiency Policy (NREEEP) and supports the global Sustainable Development Goal (SDG 7) of ensuring affordable and clean energy for all.

II. LOCATIONAL CHALLENGES TO RENEWABLE ENERGY SYSTEMS IN RURAL ABUJA

The implementation of renewable energy systems, particularly hybrid configurations, in the rural regions of Abuja encounters a variety of location-specific challenges that significantly impact their feasibility, sustainability, and operational performance. A primary obstacle is related to land accessibility and tenure. In numerous rural communities across Abuja's six area councils, especially in Abaji and Kwali, land ownership is often dictated by customary laws that frequently lack formal documentation. This situation leads to disputes, delays in land acquisition, and complications in securing long-term investments for energy infrastructure (Ikejemba & Schuur, 2018). Another critical challenge is the topographical and environmental variability present in the region. Although Abuja generally enjoys high solar irradiance, areas characterized by hilly terrain, such as certain parts of Bwari and Kuje, pose significant installation challenges for both solar panels and wind turbines. Factors such as elevation and slope gradients can affect the mounting of equipment, the construction of access roads, and the overall stability of the systems. Additionally, dense vegetation or forest cover may obstruct solar access and impede wind flow, resulting in suboptimal energy production(Okedu et al., 2024) (Akinyele & Rayudu, 2014).

The lack of adequate infrastructure further complicates the deployment of hybrid systems. Many rural communities suffer from inadequate road networks, which complicate the transportation of renewable energy equipment and increase associated costs. Furthermore, the absence of nearby substations or transmission lines restricts the functionality of hybrid systems intended to integrate with the national grid or operate as mini-grid hubs. The lack of such essential infrastructure also escalates the costs and logistical challenges associated with maintenance and technical support(Oyinna et al., 2025). Financial and socio-political factors also contribute to these challenges. Despite governmental incentives aimed at promoting renewable energy investments, many rural electrification initiatives are hindered by insufficient funding, corruption, and a lack of continuity. Local acceptance and engagement are crucial; skepticism towards external developers or unfamiliar technologies can impede or completely halt deployment efforts. Variations in education levels and awareness regarding the benefits of renewable energy necessitate comprehensive community engagement and capacity-building initiatives to facilitate successful adoption (Shaaban & Petinrin, 2014).

Security concerns, particularly in border regions of Abuja adjacent to Niger and Kogi states, introduce additional risks to the deployment and sustainability of infrastructure. Issues such as vandalism, theft of equipment, and communal conflicts can jeopardize the longevity of energy projects(Oyinna et al., 2024). Consequently, it is imperative for project developers to incorporate risk mitigation strategies into their planning processes. Lastly, climate variability and limitations in data availability also pose challenges to effective planning. The scarcity of accurate, long-term meteorological data for wind and solar resources in rural areas of Abuja often results in unreliable information, which undermines the precision of energy modeling and system design, complicating the prediction of performance and the justification of investment returns (Adaramola et al., 2014). The deployment of hybrid renewable energy systems in rural Abuja is confronted with multifaceted challenges that necessitate integrated solutions encompassing technical, legal, social, and financial dimensions to ensure successful implementation and sustainability.

III. METHODOLOGY

➢ *Description of Study Area*

The Federal Capital Territory (FCT) of Nigeria is composed of six Local Government Areas (LGAs): Abaji, Abuja Municipal Area Council (AMAC), Bwari, Gwagwalada, Kuje, and Kwali. Each LGA is subdivided into wards, which represent the smallest administrative divisions. Geographically, the FCT is situated at coordinates 9.267092° N and 7.531128° E, encompassing an area of 1,476 square kilometers, with an elevation of 360 meters (1,180 feet). According to estimates from 2022, the population of the FCT is approximately 1,693,400 individuals. The Abaji LGA, which is primarily rural, has experienced modest population growth since 2006(Ibrahim et al., 2025). In contrast, the Abuja Municipal Area Council (AMAC), recognized as the most urbanized LGA, has undergone substantial population increases attributed to urbanization and migration trends. Bwari, which hosts several educational institutions, has also

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witnessed population growth. Gwagwalada, home to the University of Abuja, has experienced significant demographic expansion. Kuje, originally a rural area, is currently undergoing a process of urbanization. Lastly, Kwali, noted for its cultural heritage, continues to maintain a predominantly rural character.

➢ *Suitability Analysis*

To evaluate the suitability of hybrid renewable energy system deployment in rural Abuja, a comprehensive GIS-based approach integrating environmental, infrastructural, and socio-economic parameters was employed. The methodology follows a structured multi-criteria decision analysis (MCDA) using the Analytic Hierarchy Process (AHP) to assign weights to different factors, followed by a weighted overlay analysis in ArcGIS to generate a spatial suitability map.

The first step involved identifying and sourcing relevant spatial datasets. Environmental parameters included solar irradiance and wind speed, obtained from the Nigerian Meteorological Agency and NASA's POWER database. Elevation and slope data were extracted from the Shuttle Radar Topography Mission (SRTM) at 30-meter resolution to account for terrain limitations. Land use/land cover (LULC) data were retrieved from the National Space Research and Development Agency (NASRDA), with reclassification to distinguish agricultural, forest, built-up, and barren land. This is shown in Figures 1-2.

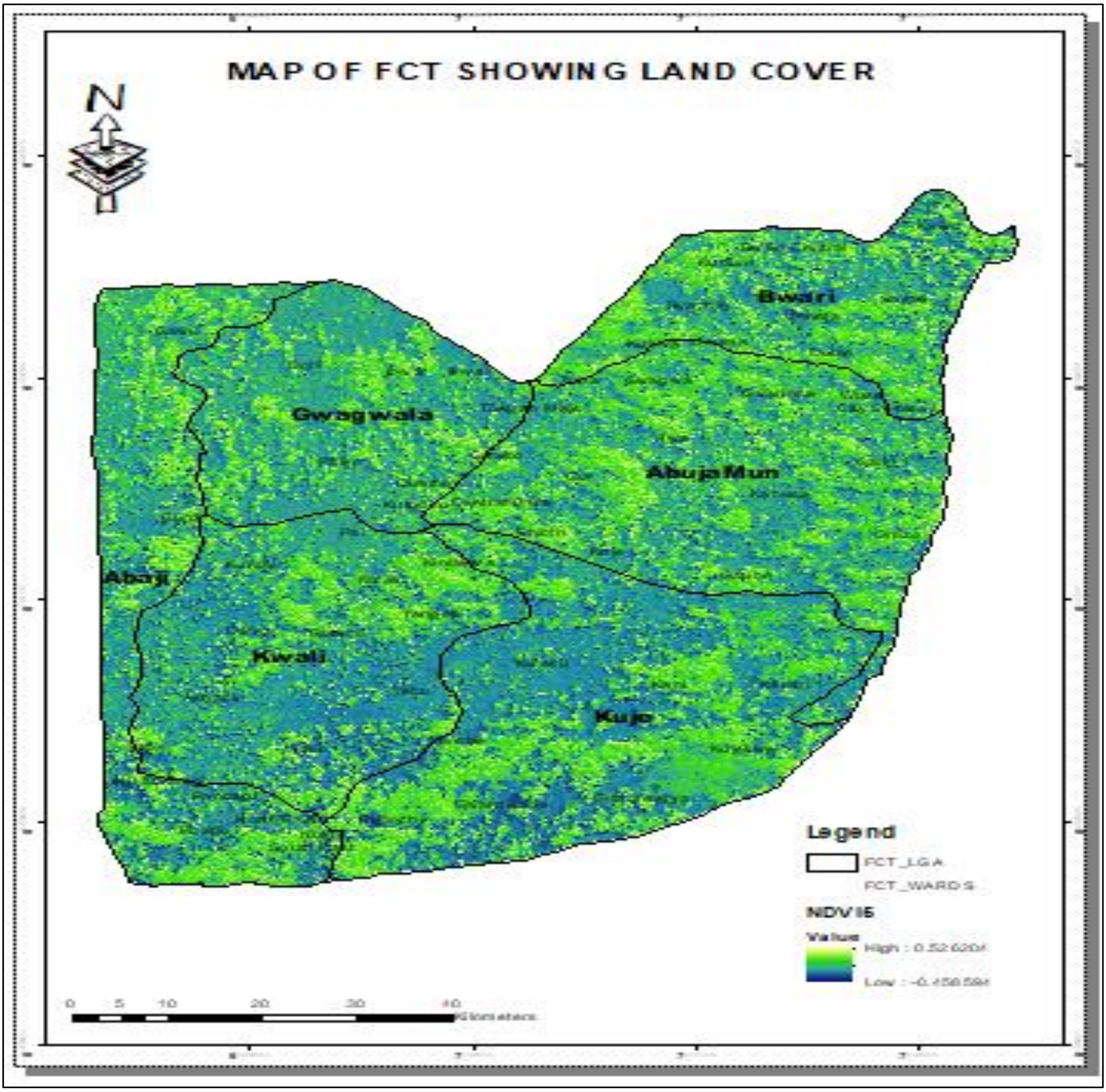

Fig 1 NDVI Map for FCT Showing Forest Areas, Grasslands, Water Bodies and Buit-up Areas and Baren Lands.

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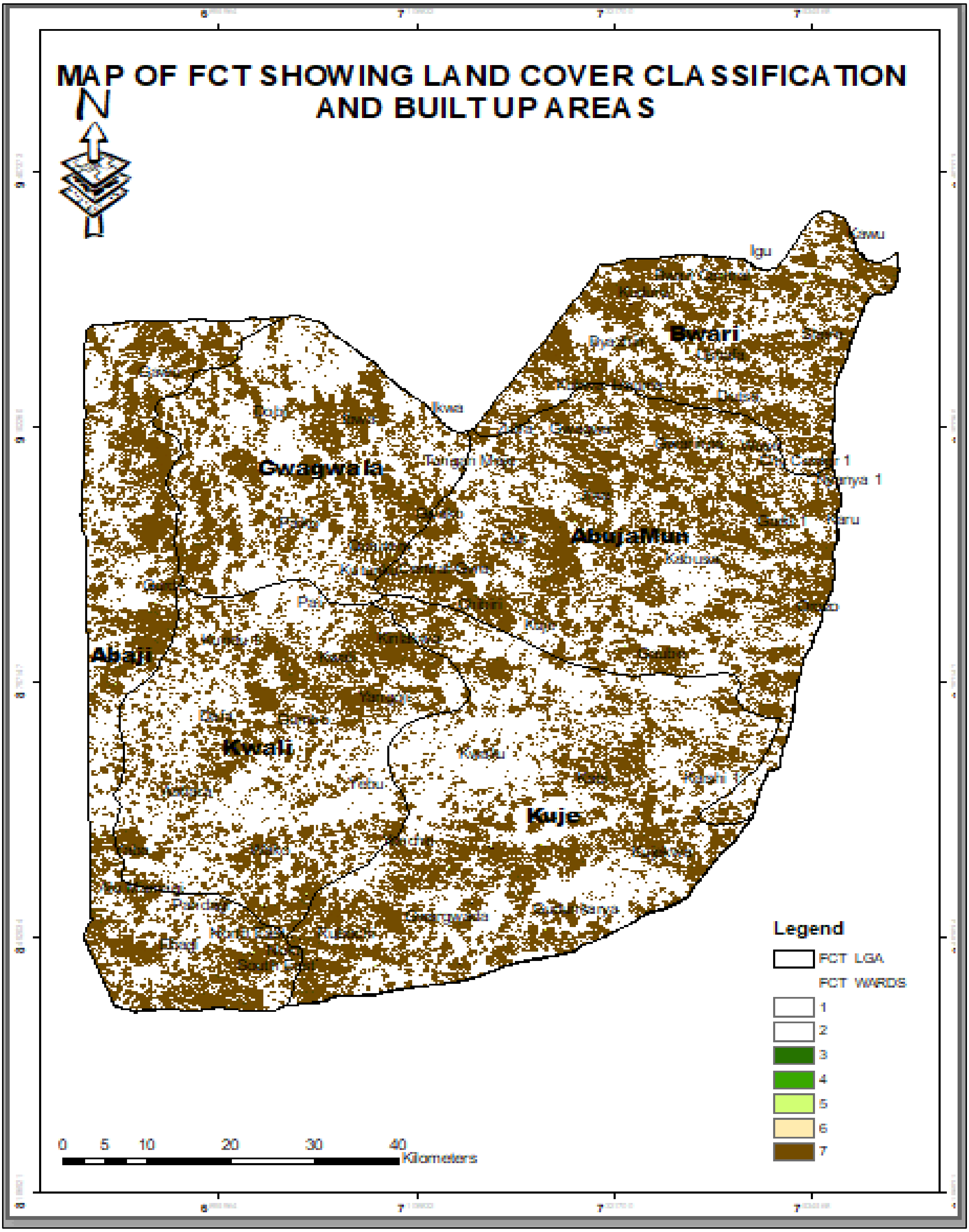

Fig 2 Reclassified LULC Map showing built-up areas and barren lands as priority areas

The figure 3 shows the geospatial aggregation of biomass, wind and solar resources, in the FCT from the primary data collected from the field, and from Nigerian Meteorological Agency (NiMet).

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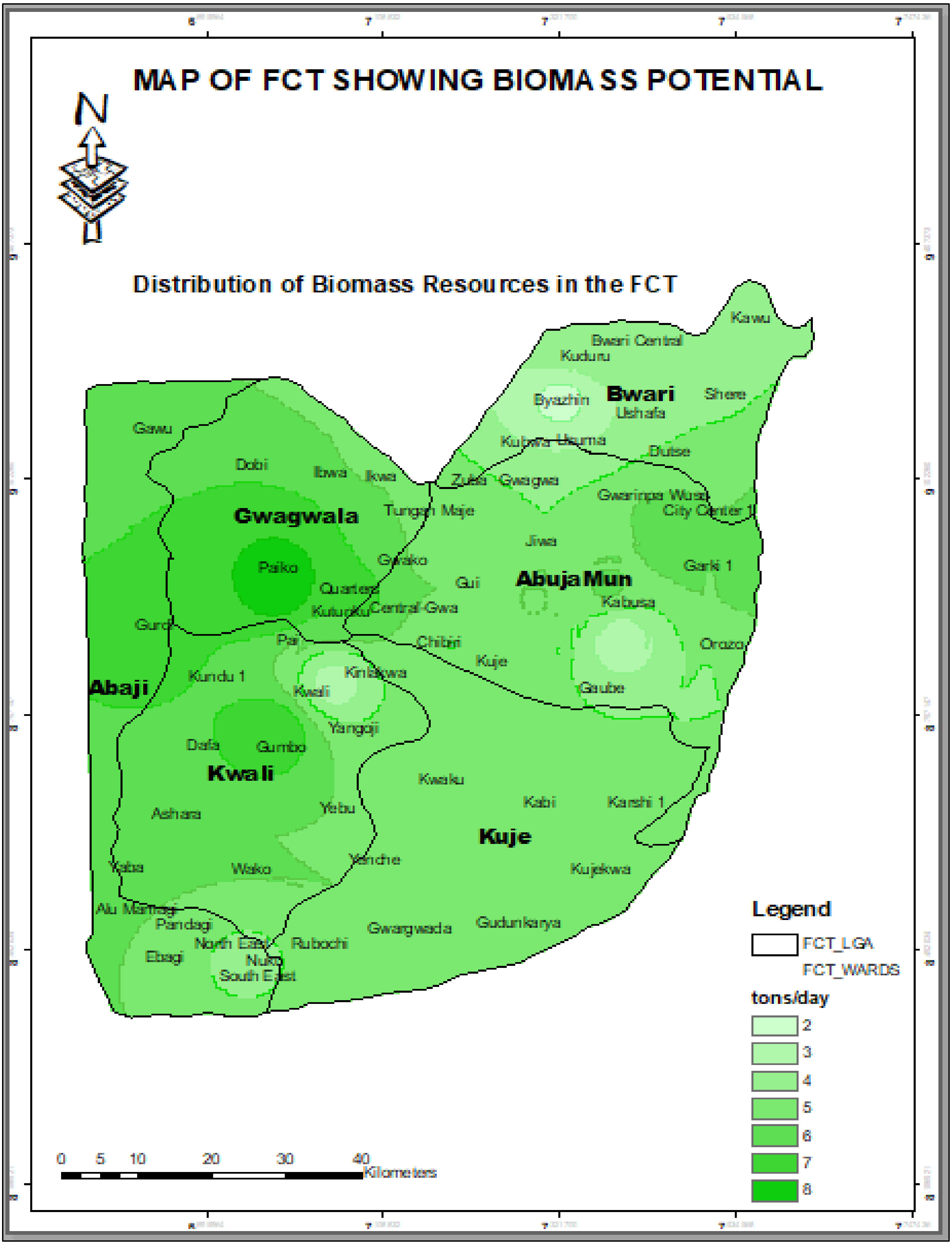

Fig 3 FCT Biomass Raster
(Ibrahim et al., 2025)

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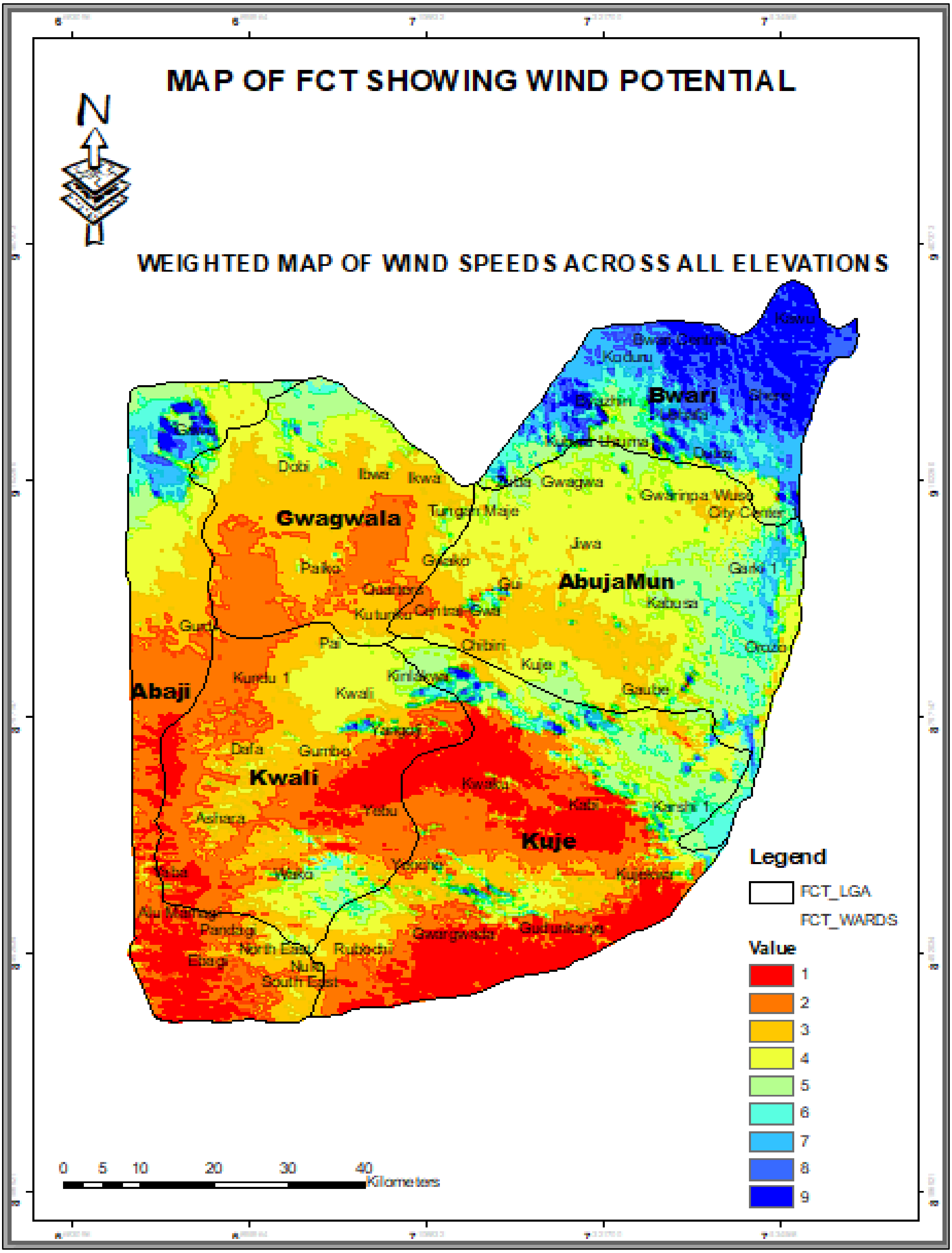

Fig 4 FCT Wind Raster
(Ibrahim et al., 2025)

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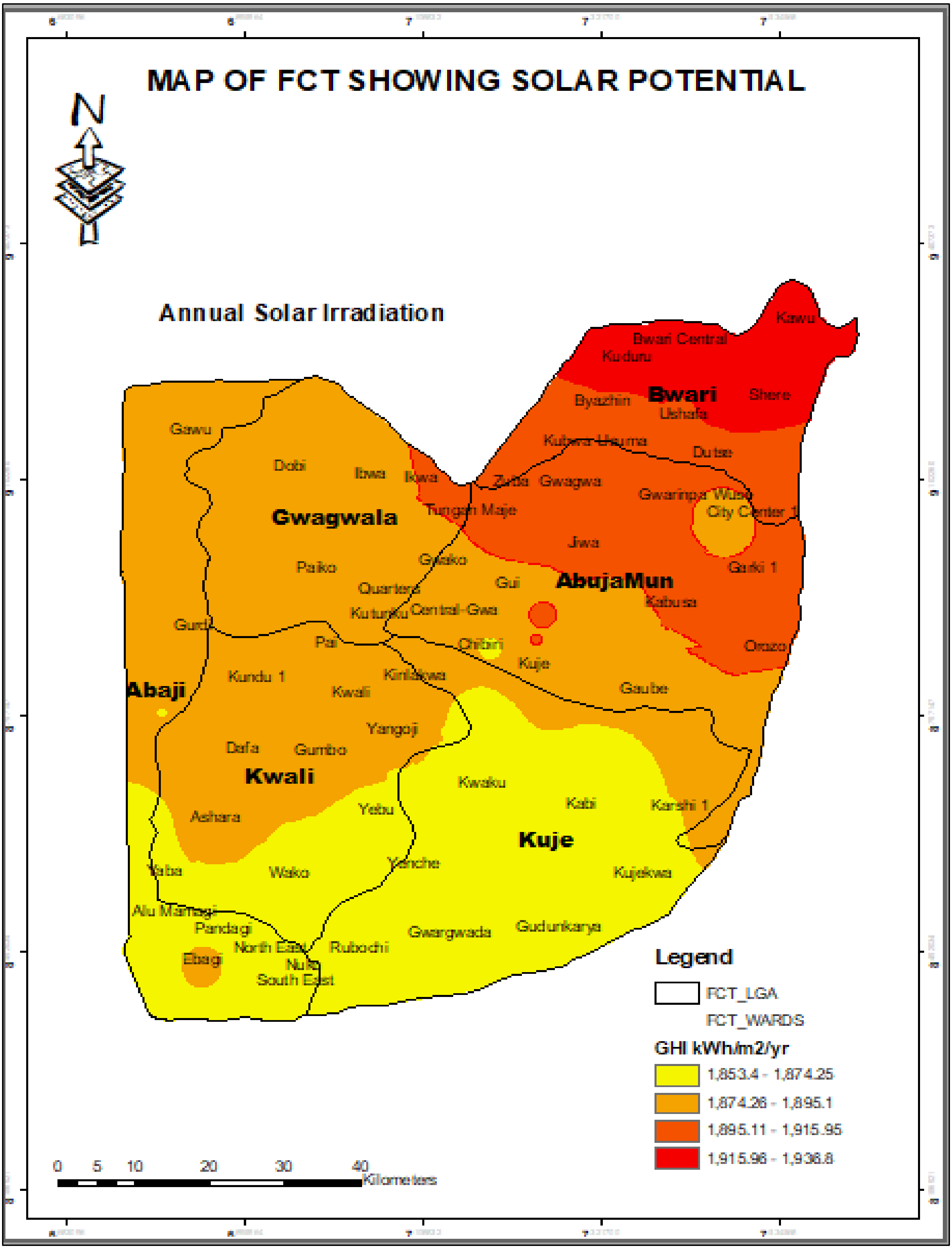

Fig 5 FCT Solar Raster
(Ibrahim et al., 2025)

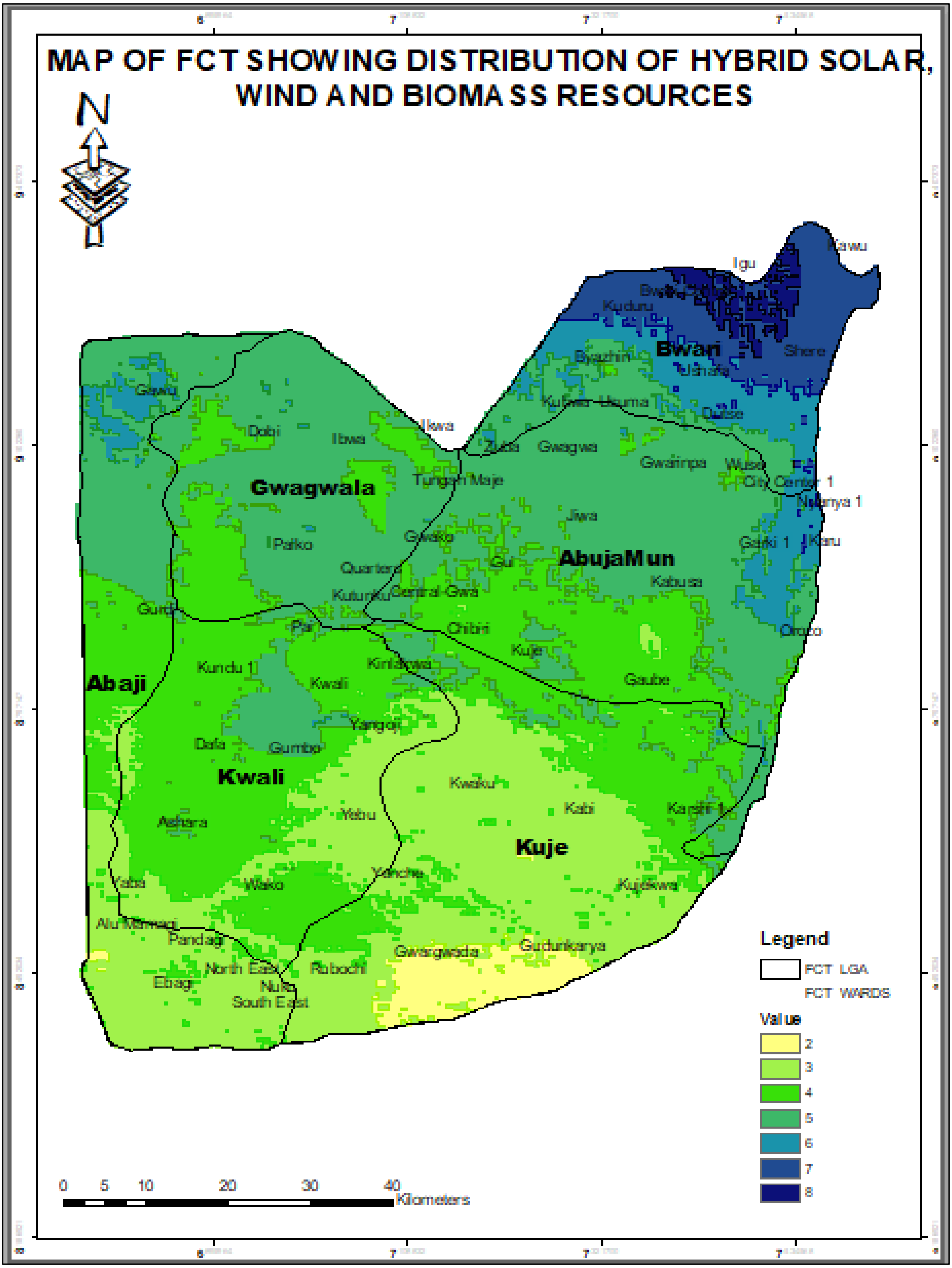

Fig 6 Weighted Map of Combined Solar, Wind and Biomass Resources in the FCT

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Subsequently, all raster layers were reclassified based on their standardized scores and integrated through a weighted overlay process in ArcGIS.

$$SA_i = W_i \times LULC\,;\ i = (hybrid\ renewable\ reosurces) \quad (1)$$

Where, SA_i represents suitability area, W_i represent weighted scores on the solar wind, biomass and $LULC$ represents land use and land cover. A suitable area for a hybrid renewable energy system is defined by the following parameters.

- Availability of renewable energy resources (Solar, Wind, Biomass)
- Availability of a built-up area for construction

The LULC raster is obtained by reclassifying the Landsat 8 image obtained from United State Geological Survey Platform by the Normalized Difference Vegetation Index (NDVI) ranges with values range from -1 to +1, with negative values. Values from; -0.018 to 0.015 indicates area characterized by water, and 0.015 to 0.14 indicates built-up area (Oyinna & Ukoba, 2024). Table 1 shows the reclassification of the LULC raster.

Table 1 Reclassification of LULC raster

Classification	Label	NDVI Range	Colours
2	Water body	-0.018 –0.015	Lapiz Lazuli Blue
7	Built up area	0.015 – 0.14	Rose Quartz
6	Barren land	0.14 – 0.18	Sahara sand
5	Shrub and grass land	0.18 – 0.27	Lemongrass yellow
4	Sparse vegetation (Crop area)	0.27 – 0.36	Leaf green
3	Dense vegetation (Forest area)	0.36 – 0.70	Fir green

➢ *Socio-Economic Analysis*

Socio-economic data, including population density and electrification rates, were obtained through field surveys. A survey was conducted across six LGAs in the FCT covered 294 respondents from various rural communities. The demographic profile indicates a relatively educated population, with 53.1% having tertiary education and 85.4% possessing intermediate knowledge of renewable energy systems. The majority (69%) were male, and the primary occupations included civil service (36.7%), students (26.5%), and trading (23.8%).

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IV. RESULTS AND DISCUSSIONS

➢ *Suitable Location for Hybrid Renewable Energy Systems*

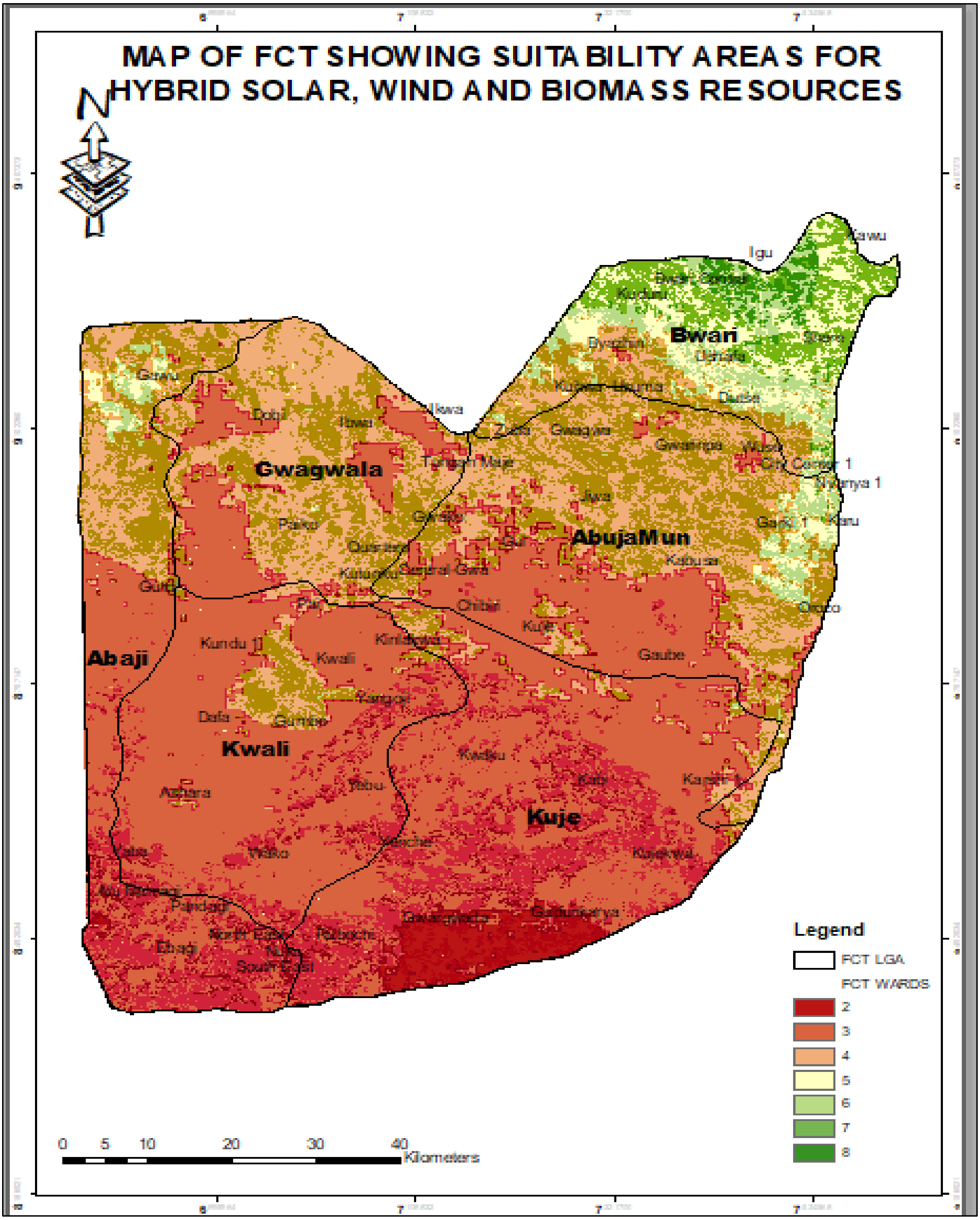

Fig 7 Map Showing Locations Suitable for Hybrid Renewable Resources

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The suitability analysis as shown in Figure 7 shows the product of the Weighted hybrid renewable energy resources map and the Land Use Land Cover (LULC) reclassified map and depicts a convergence of areas with the highest classification of hybrid resources and built-up areas as contained in the NDVI classification shown in Rose Quartz colour. The green colour on the map shows areas with a great probability of citing hybrid solar PV-Wind-Biomass system, while the red colour shows unsuitable areas. Bwari LGA (Bwari Central, Shere, Kurudu, Igu, Kawu) , Gwagwalada LGA (Gawu) and Abuja Municipal Area (Karu, Garki 1, Orozo and Nyanya) were identified as suitable areas for a hybrid. Kuduru Village in Bwari Area Council of the FCT with coordinates 9.2734, 7.3178 with solar irradiation of 1928.10 $kWh/m^2/yr$, mean wind speed of 5.79 m/s at 200m, average biomass resources of 2.9, 3.7, 3.1 and 3.4 tons/day for Poultry Waste, Cow Dung, Agro Waste and Food Waste respectively giving a total of 13.3tons/day of Biomass was selected for further socio-economic analysis..

Following the response from the questionnaire distributed for the socio-economic analysis of the study on hybrid renewable energy systems (HRES), the results were analyzed as follows:

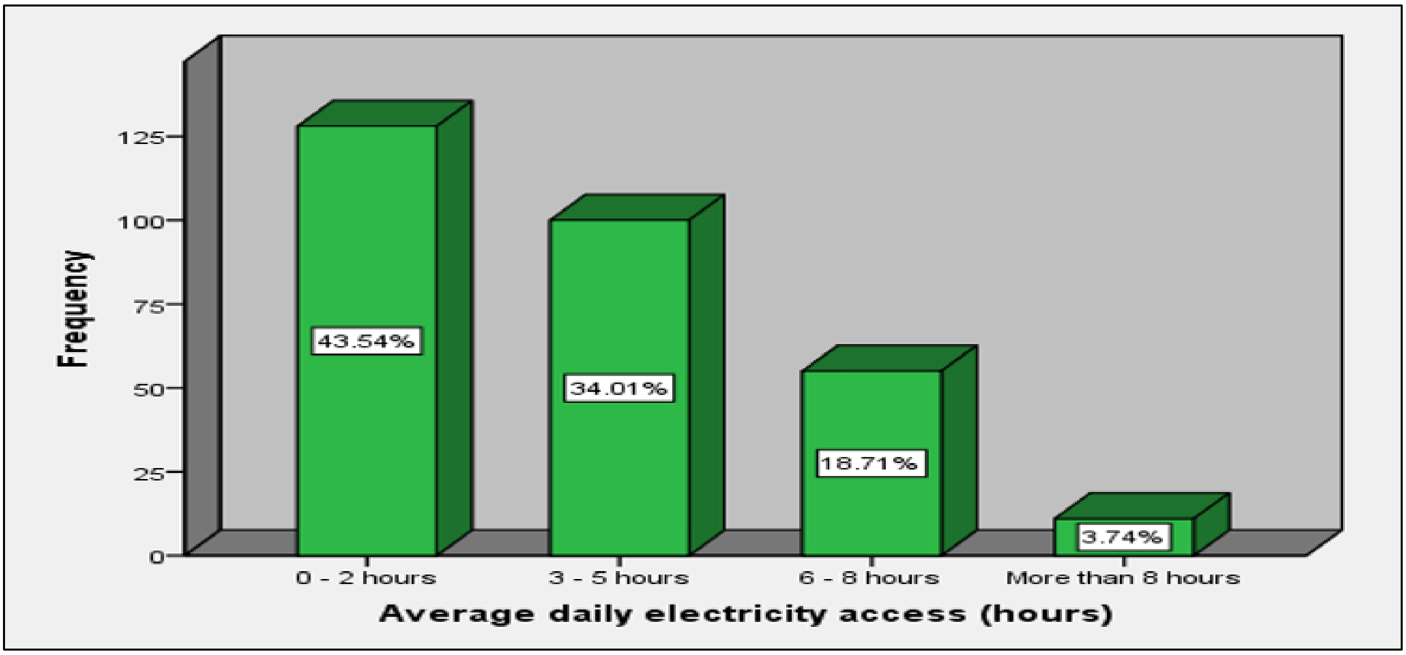

Fig 8 Average Daily Electricity Access in the FCT

Current energy access is limited, with 43.5% of respondents accessing electricity for only 0–2 hours daily. Primary energy sources are largely traditional and polluting: 35% use firewood, 32% rely on diesel generators, and only 1.4% use solar energy. Monthly energy expenditures show that over half (52.4%) spend between ₦2,000 and ₦5,000, and 12.9% spend more than ₦10,000.

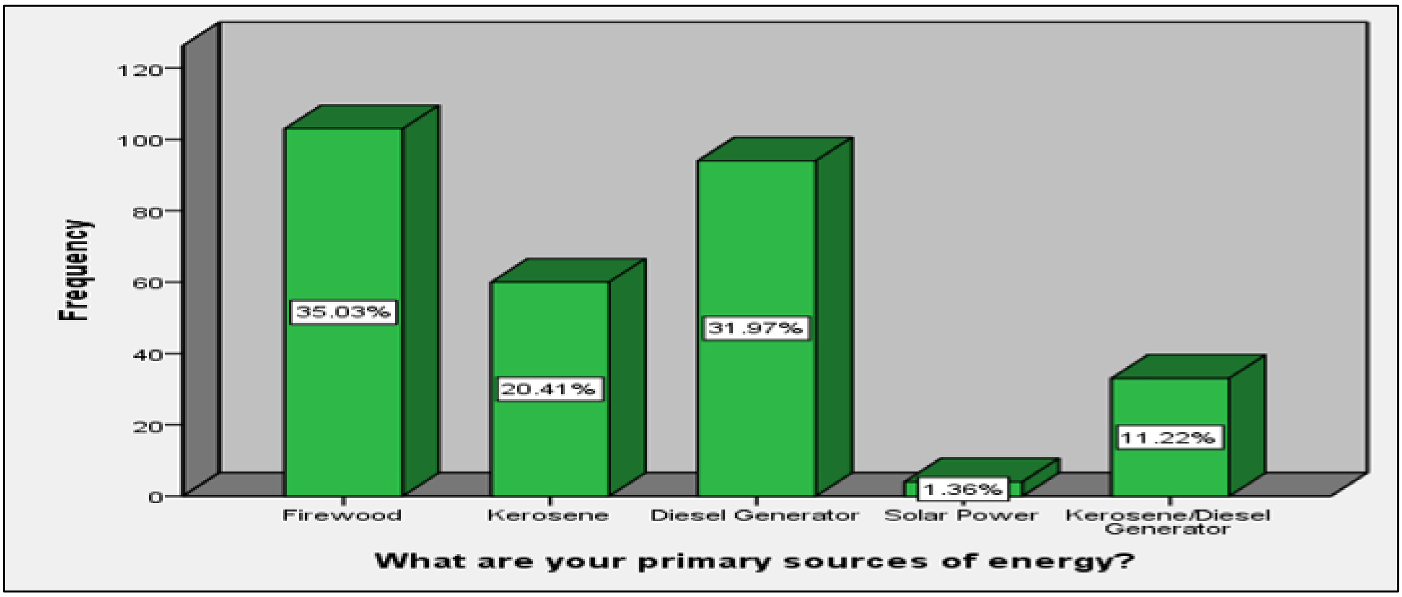

Fig 9 Primary Sources of Energy in the FCT

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Awareness and interest in renewable energy are high as about 86.4% believe renewable energy could benefit their community, and 91.2% are willing to contribute financially to access it. Notably, 37.1% are ready to pay between ₦5,000 and ₦10,000 monthly. Expected benefits include reliable electricity access (58.2%), environmental improvements (21.8%), and job creation (11.6%).

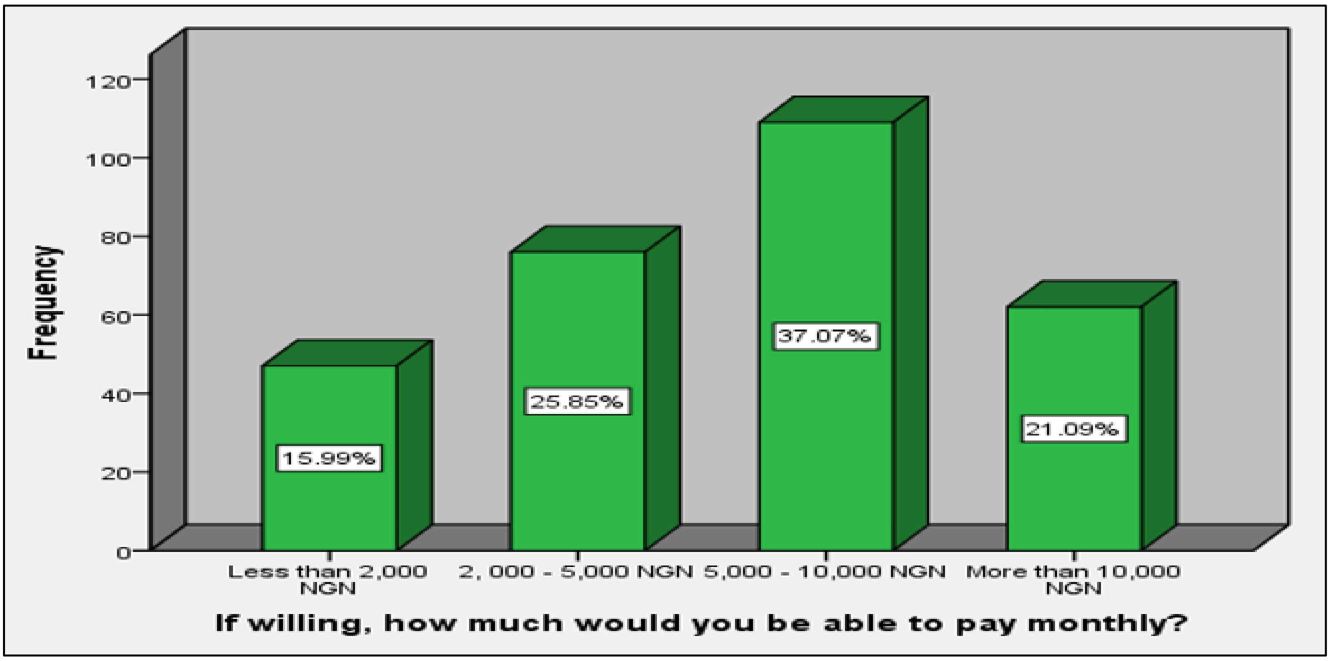

Fig 10 Willingness to Pay

Biomass resources such as Poultry waste and agricultural residues are prevalent, with 54.8% reporting over 10 tons of poultry waste generated daily. About 90.5% confirm the presence of infrastructure for biomass processing.

Challenges to HRES deployment identified include maintenance and reliability concerns (34.7%), high installation costs (27.9%), and lack of technical knowledge (16.7%). Despite these, 85.4% believe their communities could maintain a renewable system with proper support. Preferred energy sources include solar (63.6%), wind (27.9%), and biomass (8.5%). When asked about design priorities, 41.8% emphasized cost-effectiveness, reliability, and environmental benefits. Additionally, 83% suggested awareness and training as key to project success.

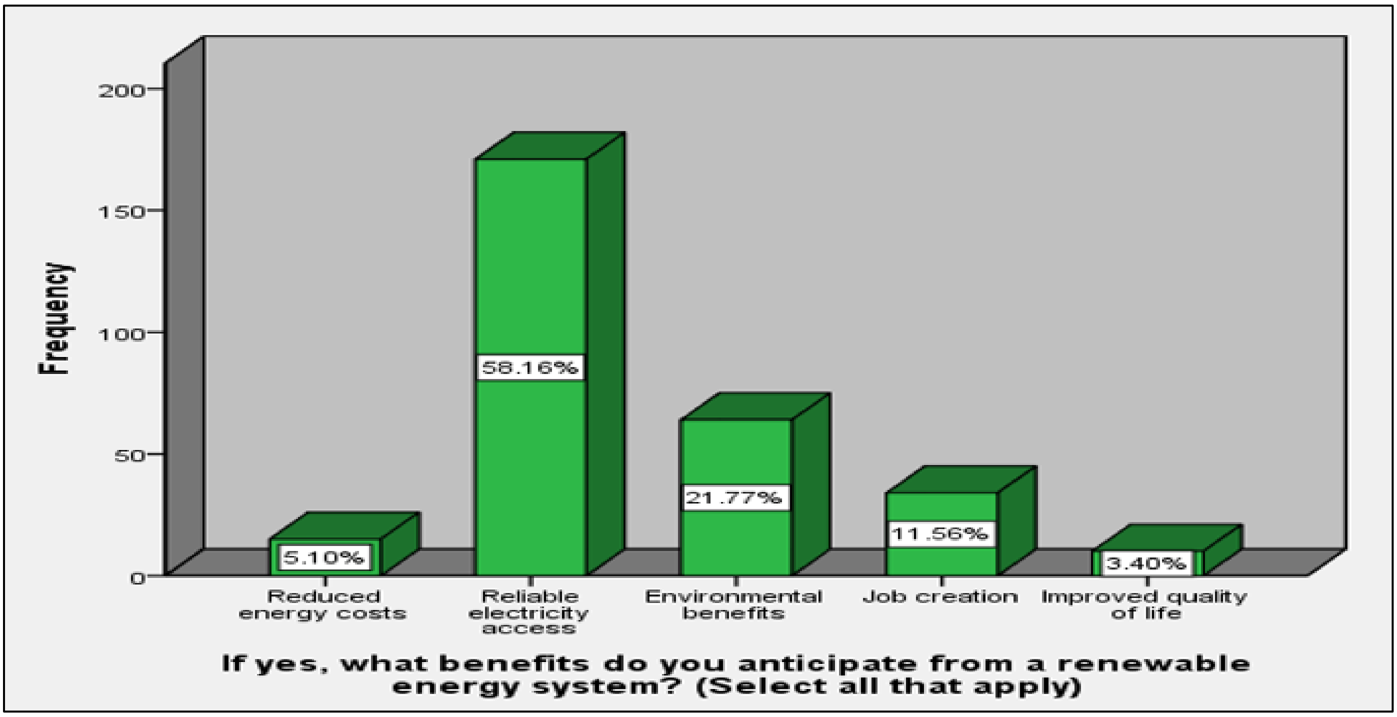

Fig 11 Benefits of HRES in the FCT

The study revealed that energy poverty remains a significant issue in rural FCT, with over three-quarters of the population having access to electricity for less than 6 hours daily and relying on expensive and polluting fuels. However, the community demonstrates strong awareness, interest, and financial willingness to adopt Hybrid Renewable Energy Systems.

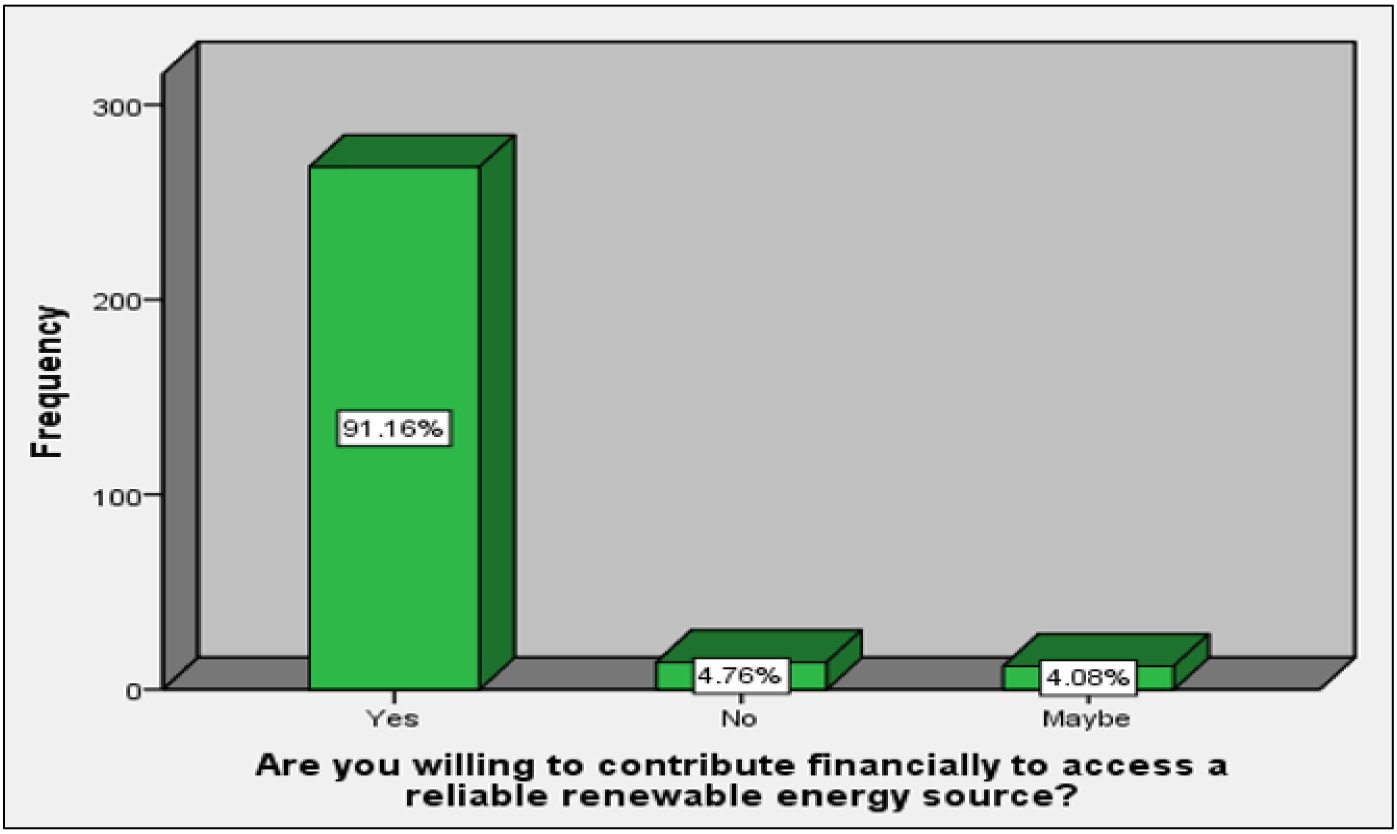

Fig 12 Social Acceptance

Moreover, there exists considerable potential for the utilization of solar and biomass resources, bolstered by the availability of local waste streams and the existing infrastructure that can facilitate biomass energy development. Survey participants anticipate a range of socio-economic advantages, such as enhanced reliability, job creation, and improved living standards. The level of social readiness is notably high, with communities expressing a willingness to engage in training and maintenance programs.

However, despite these favorable indicators, there are substantial obstacles to overcome. These challenges include the prohibitive costs associated with the installation of hybrid renewable energy systems (HRES), gaps in technical knowledge, and apprehensions regarding maintenance. Respondents identified community ownership models, technical training, and ongoing maintenance support as essential factors that could significantly contribute to the success of such projects.

V. CONCLUSION AND RECOMMENDATION

This study successfully conducted a suitability analysis combining solar, wind, and biomass resource layers to identify Bwari (including Kurudu, Shere, Igu, and Kawu), Gwagwalada (Gawu), and Abuja Municipal Area Council (Karu, Orozo, Garki 1, and Nyanya) as the most promising locations for hybrid energy system deployment. The socio-economic analysis shows that energy access in rural FCT is limited, with 43.5% of respondents having limited access to electricity for 0-2 hours daily. Primary energy sources are traditional and polluting, with 35% using firewood, 32% relying on diesel generators, and 1.4% using solar energy. Most respondents are aware of renewable energy, with 86.4% believing it could benefit their community. Biomass resources, such as poultry waste and agricultural residues, are prevalent, with 91.2% willing to contribute financially. Challenges to HRES deployment include maintenance and reliability concerns, high installation costs, and lack of technical knowledge. preferred energy sources include solar, wind, and biomass. Design priorities include cost-effectiveness, reliability, and environmental benefits. Social readiness is high, with communities open to participating in training and maintenance initiatives. However, barriers include high installation costs, technical knowledge gaps, and maintenance concerns. Community ownership models, technical training, and regular maintenance support are critical enablers of project success.

The study suggests that hybrid renewable energy projects should be prioritized in rural communities to achieve energy security and stimulate local development. Future studies should expand biomass and wind data collection to improve energy planning accuracy. System designs should incorporate community-specific load profiles and account for seasonal variations. Capacity building initiatives should focus on geospatial analysis and remote sensing technologies. Hybrid systems should integrate energy storage solutions and longitudinal studies on renewable resource variability. To deploy HRES effectively, government and NGOs should provide subsidies, promote technical training programs, educate rural communities on renewable energy benefits, expand infrastructure development, and encourage public-private partnerships.

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