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Enhancing Urban Landscapes With Smart Energy Technologies: A Focus On Power Engineering

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ABSTRACT

Abuja, Nigeria's capital faces critical energy challenges due to the nation's dependence on traditional fossil fuels and an unreliable power grid. The city has significant potential for renewable energy integration, particularly solar power, given its high levels of solar radiation. This paper explores the innovative incorporation of energy storage and renewable energy systems into urban landscaping elements, such as parks, rooftops, and public spaces, to address these energy challenges. The study investigates the feasibility of integrating technologies like solar photovoltaic (PV) systems, small wind turbines, and battery storage into the city's green infrastructure. Through the lens of power engineering, the paper examines how these elements can improve energy reliability, reduce grid dependence, and promote environmental sustainability. The method of data collection adopts the secondary typology of data collection which includes review of records, publications and other authoritative documents to elicit data in inline with the research. The research further evaluates the technical, infrastructural, and regulatory challenges of implementing these solutions in Abuja's urban spaces. The study's findings demonstrate that integrating energy storage systems in urban landscapes can contribute to a resilient and sustainable energy future for Abuja, supporting the city's growth while mitigating the environmental impacts of fossil fuel reliance.

Keywords: Renewable energy, Energy storage, Solar power, Urban landscaping & Sustainability

INTRODUCTION

Abuja, Nigeria's capital faces significant energy challenges due to the country's over-reliance on traditional energy sources like oil and natural gas. Despite Nigeria's status as one of the world's largest oil producers, its power sector suffers from inefficiencies, resulting in frequent blackouts and unstable grid infrastructure. The unreliable electricity supply affects both the residential and commercial sectors, often leading to widespread use of diesel generators, which have environmental and economic downsides (Kehinde et al., 2018). With growing urbanization and population increases, Abuja's energy demands continue to rise, putting further pressure on an already strained energy system. Nigeria, particularly in the northern regions like Abuja, enjoys high solar radiation, receiving an average of 5.5 kWh/m² of solar energy per day (Sambo, 2009). This makes the city well-positioned to capitalize on renewable energy technologies such as solar power. Harnessing these resources can provide a much-needed alternative to traditional power sources, contributing to a more sustainable energy mix and reducing the reliance on fossil fuels (Ugwu et al., 2022).

As Abuja's urban landscape develops, the integration of energy storage systems into

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green spaces becomes crucial for addressing the city's power challenges. Parks, gardens, and other landscaping elements in urban settings offer an innovative opportunity to house renewable energy storage solutions. These green areas can host solar panels, small wind turbines, and battery storage systems, thereby making efficient use of space while promoting clean energy (Oyedepo et al., 2018). Energy storage systems, particularly solar batteries, play a vital role in stabilizing the energy supply by mitigating the intermittency of renewable energy sources. The variability of solar energy generation, which peaks during the day, can be balanced by storing excess energy and releasing it during periods of lower production, such as at night or during cloudy conditions (Chanchangi et al., 2022). For a city like Abuja, where energy infrastructure is often unreliable, integrating renewable energy storage within urban landscaping could provide a practical solution to ensure consistent electricity supply, reduce grid dependence, and enhance environmental sustainability (Amadi & Igbogidi, 2024).

This study explores how urban landscaping elements in Abuja, such as parks, recreational areas, and green rooftops, can serve as hosts for renewable energy storage systems. It investigates the feasibility of incorporating technologies like solar photovoltaic (PV) systems, wind turbines, and battery storage into the city's green spaces. These elements offer a dual function—contributing to urban aesthetics and fulfilling practical energy storage needs (Ogunniyi et al., 2023). The research further examines the renewable energy potential of Abuja, particularly focusing on solar energy, which remains underutilized despite its vast availability. Through the lens of power engineering, the study analyzes how energy storage systems can be integrated into the landscape and how urban planners can design energy-efficient cities (Okedu et al., 2015). Additionally, the study evaluates the current regulatory and infrastructural challenges that hinder the widespread adoption of renewable energy technologies in Nigeria.

LITERATURE REVIEW

Energy Storage Technologies

Energy storage systems are crucial for managing energy supply and demand in urban environments, particularly with the integration of renewable energy sources like solar and wind power. These systems capture excess energy produced during peak periods and store it for later use, addressing the intermittency of renewable energy. Several energy storage technologies are highly relevant for urban landscapes, each offering unique benefits and challenges.

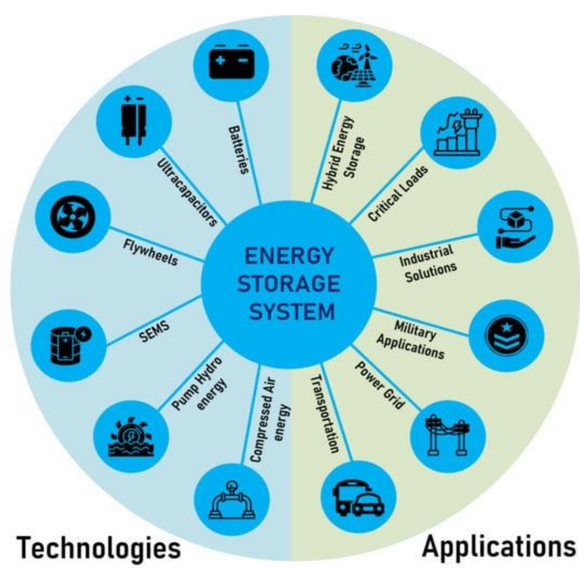

Figure 1: Energy Storage System (Anastasovski et al., 2024).

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1. Solar Panels and Battery Systems - Solar panels paired with battery storage systems are one of the most prevalent energy solutions in urban areas. Solar photovoltaic (PV) systems capture solar energy and store it in batteries for use when demand exceeds supply, making them highly suitable for decentralized energy generation (Koohi-Fayegh & Rosen, 2020). Lithium-ion batteries are often favored in these systems due to their high energy density, efficiency, and longevity. In urban areas such as Abuja, where solar radiation is abundant, solar battery systems provide a practical means of reducing dependence on the national grid while enhancing energy reliability (Elalfy et al., 2024).
2. Lithium-Ion Batteries - Lithium-ion batteries have emerged as a dominant technology in energy storage due to their superior energy density, long cycle life, and versatility (Anastasovski et al., 2024). These batteries are commonly integrated into renewable energy systems, especially in solar PV setups, to store energy during times of high production and discharge it during high demand periods. However, the relatively high cost and resource constraints of lithium-ion batteries present challenges for widespread adoption in developing regions like Nigeria (Kalaiselvam & Parameshwaran, 2014). Their integration into urban landscapes remains a key focus for improving sustainability.
3. Flywheels - Flywheel energy storage systems store energy in the form of kinetic energy and release it as needed, offering rapid response times and high efficiency. These systems are particularly useful for grid stabilization and frequency regulation but have limited capacity for long-term storage (Elalfy et al., 2024). In urban landscapes, flywheels can be integrated into parks or green spaces where they can contribute to local renewable energy systems, providing short bursts of power during fluctuations. Their applicability in cities like Abuja could be further explored for grid support and urban resilience.
4. Thermal Energy Storage - Thermal energy storage (TES) systems store heat or cold energy for later use, offering a sustainable way to manage energy for heating, cooling, and power generation in urban areas (Gude, 2023). TES can be integrated into urban infrastructure, such as public buildings or district heating systems, where solar or waste heat is stored for nighttime or overcast periods. In regions with high solar potential like Abuja, TES can play a crucial role in reducing reliance on conventional energy sources for air conditioning and heating (Koohi-Fayegh & Rosen, 2020).
5. Microgrids - Microgrids are small, localized energy grids that can operate independently of the national grid, often integrating various renewable energy sources and storage technologies. In urban areas, microgrids enhance energy reliability by providing power during grid outages or peak demand periods (Shahzad et al., 2023). They are particularly suited for decentralized

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renewable energy systems in cities, where solar, wind, and energy storage can be integrated into parks, residential areas, and commercial zones. The flexibility of microgrids in utilizing different energy sources makes them a vital element in sustainable urban design (Judge et al., 2022).

Power Engineering in Urban Design

Power engineering plays a critical role in ensuring efficient energy distribution in urban landscapes, where renewable energy integration is becoming increasingly essential. The key methods of integrating power engineering into urban design focus on decentralizing energy generation, enhancing grid flexibility, and incorporating smart energy solutions (Judge et al., 2022).

1. Decentralized Energy Systems and Microgrids - Decentralized energy systems are crucial in urban landscapes, as they generate energy close to the point of consumption, reducing transmission losses and increasing resilience. Microgrids are particularly useful in cities, where they can operate independently from the national grid and integrate renewable energy sources such as solar and wind. By connecting parks, schools, and residential areas to localized energy systems, cities can enhance energy security and reduce reliance on fossil fuels (Barman et al., 2023).
2. Solar Photovoltaic (PV) Systems - Solar PV systems are widely used in urban environments due to their scalability and ability to integrate seamlessly into urban infrastructure, such as rooftops, parking structures, and public spaces (Koohi-Fayegh & Rosen, 2020). Solar PV systems generate clean energy during daylight hours and, when paired with energy storage, provide a continuous power supply. In Abuja, solar PV systems have the potential to significantly reduce the city's dependence on traditional energy sources (Elalfy et al., 2024).
3. Wind Energy Integration - Small-scale wind turbines, particularly vertical-axis wind turbines (VAWTs), are increasingly being integrated into urban environments where space is limited. VAWTs can operate in turbulent airflows typical of built-up areas, making them suitable for parks and open spaces (Alam & Jin, 2023). The combination of wind and solar energy can create hybrid systems that ensure a steady supply of renewable energy in urban settings.

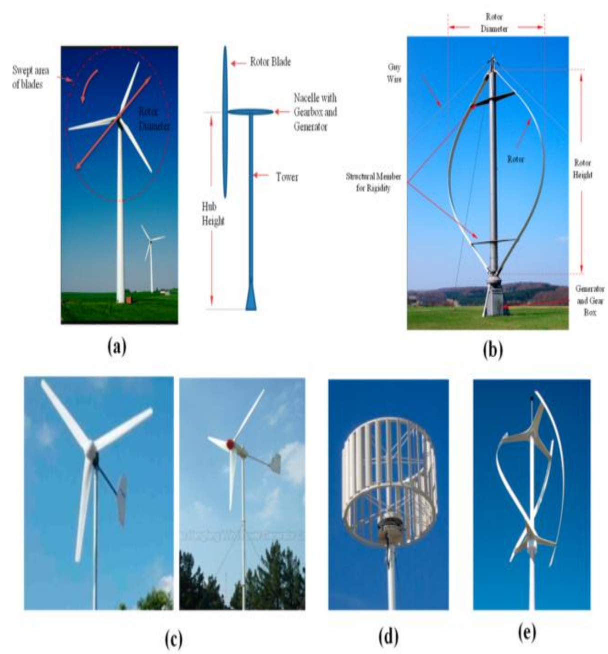

Figure 2: Typologies of Turbines for Wind Energy Integratuion (Alam & Jin, 2023)

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4. Smart Grid Technologies - Smart grids enable real-time monitoring and control of energy distribution, making them essential for managing the variability of renewable energy sources in urban areas (Judge et al., 2022). By integrating sensors, meters, and automated control systems, smart grids can optimize the distribution of electricity, reduce energy waste, and improve the efficiency of microgrids. The implementation of smart grids in Abuja could enhance the city's energy resilience and promote sustainable urban growth (Wee et al., 2012).
5. Electric Vehicle (EV) Charging Infrastructure - As electric vehicles become more prevalent, the integration of EV charging stations into urban landscapes is a key component of sustainable urban design. EV charging stations can be powered by renewable energy sources, such as solar and wind, connected to local microgrids or the broader grid (Barman et al., 2023). This infrastructure reduces reliance on fossil fuels and supports the transition to cleaner transportation systems in cities like Abuja.

Integrating power engineering into urban design is vital for creating sustainable and resilient cities. Decentralized systems like microgrids, renewable energy technologies like solar and wind and smart grid infrastructure are essential tools for optimizing energy use in urban environments. By embracing these technologies, cities can reduce their carbon footprint, improve energy reliability, and create a more sustainable urban (Ward & Walsh, 2010).

MATERIALS AND METHODS

Introduction

Abuja, the capital of Nigeria, is strategically located in the central Federal Capital Territory (FCT) with coordinates approximately 9.0578° N latitude and 7.4951° E longitude. The city's varied topography, featuring hills, plateaus, and plains with elevations ranging from 300 to over 800 meters above sea level, creates diverse microclimates and landscape features. Abuja experiences a tropical wet and dry climate with average temperatures between 23°C and 33°C and annual rainfall around 1,200 mm. This climate supports a range of vegetation types and affects the efficiency of energy storage systems integrated with landscaping. The city's modern infrastructure, including extensive green spaces such as parks and recreational areas, complements its potential for energy storage applications. The well-planned urban layout, with its residential, commercial, and governmental zones, combined with its ample sunlight, provides ideal conditions for deploying solar-powered energy storage systems in urban green spaces.

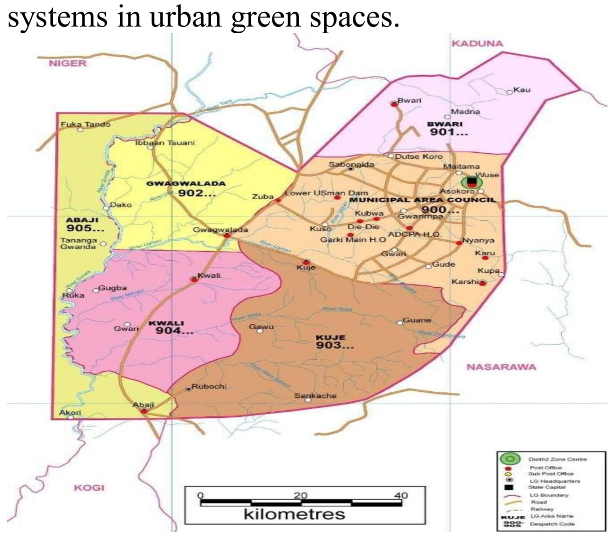

Figure 3: Study Area: Abuja, Nigeria (Ozioma, 2017)

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Data Collection

Data collection relied on secondary sources to assess urban landscape elements in Abuja as illustrated below:

Table 1: Secondary Sources Reviewed (Author)

Data Source	Type of Data	Purpose
Electricity providers, government reports, local surveys	Energy usage statistics	Understanding energy consumption patterns
Meteorological stations, local weather agencies	Solar radiation and wind data	Evaluating potential for integrating solar and wind energy solutions into urban landscaping
Planning documents, academic publications, other reports	Case studies and research papers on urban landscapes and landscape management	Gathering insights from research and case studies

RESULTS AND DISCUSSION

Energy Usage Statistics in Abuja

The energy consumption patterns in Abuja, Nigeria, in 2023 showed fluctuations throughout the year. Data revealed that February recorded the highest energy consumption at approximately 350,000 MWh, while July saw the lowest consumption, just under 300,000 MWh. The pattern of energy use did not follow the typical assumption that the dry season (November to March) would see consistently higher consumption; instead, the peak demand period occurred earlier in the year. The mid-year months (July to September) experienced a noticeable decline, potentially attributed to seasonal changes affecting industrial and residential energy demand [see table 2 & fig. 4].

Table 2: Energy Consumption Partern in Abuja (IEA, 2024)

Month	Energy Consumption (MWh)
January	320,000
February	350,000
March	340,000
April	330,000
May	320,000
June	310,000
July	290,000
August	300,000
September	310,000
October	320,000
November	330,000
December	340,000

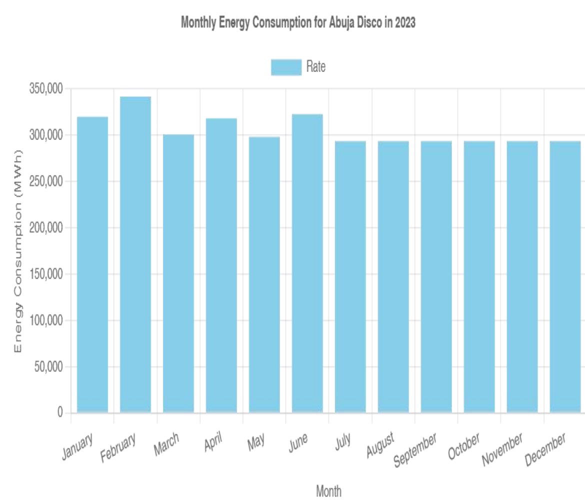

Figure 4: Monthly Energy Consumption Partern for Abuja Discos in 2023 (Energy Commission of Nigeria, 2024)

This data highlights the importance of integrating renewable energy sources and storage solutions to ensure efficient energy management and to alleviate pressure on

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Abuja's grid, which remains heavily reliant on non-renewable sources.

Available Renewable Resources in Abuja Solar

Nigeria benefits from significant solar potential, with average annual global horizontal irradiation ranging between 1,600 and 2,200 kWh/m². Abuja, located in central Nigeria, falls within this high solar resource zone. According to IRENA, Nigeria's technical potential for solar photovoltaic (PV) is estimated at 210 GW, with only 1% of suitable land considered for development (IRENA & AfDB, 2022). Concentrated solar power (CSP) also holds promise, with a technical potential of around 88.7 GW, primarily in northern regions (Ogunmodimu, 2013), though Abuja's geographic location makes PV a more feasible option.

Wind

Wind potential in Nigeria is moderate, with wind speeds at 10 meters height ranging between 2.1 m/s and 8 m/s. While Abuja's wind speeds are less favorable than northern areas, there remains a technical potential of 3.2 GW for wind power if 1% of suitable land is used (IRENA & AfDB, 2022). Northern Nigeria experiences the highest wind speeds, exceeding 7 m/s, while Abuja's potential is moderate but could still contribute to the country's renewable mix.

Hydro

Nigeria boasts a large hydropower potential of approximately 24 GW for large-scale projects and 3.5 GW for small-scale hydropower, though this capacity remains underutilized. As of 2015, Nigeria had an installed capacity of 1.9 GW from large hydro and about 60 MW from small hydro projects (IHA, 2021; U.S. Department of Trade, 2021). Abuja, situated near several rivers, could benefit from small-scale hydro developments as part of a localized energy strategy.

Overall Renewable Energy Potential

Nigeria as a whole has significant renewable energy potential, with solar photovoltaic (PV) potential estimated at 210 GW, considering only 1% of the suitable land can be utilized for project development The focus on renewable energy, particularly solar, is crucial for addressing the energy challenges in Abuja and the broader Nigerian context, given the unreliable and erratic nature of the current grid electricity supply (IRENA & AfDB, 2022).

Urban Landscape Elements Suitable for Energy Storage Systems in Abuja

Abuja's urban landscape offers a range of potential sites for the deployment of energy storage systems, notably in its parks, public gardens, and rooftops of commercial and governmental buildings. The city's planned design incorporates numerous open spaces, with approximately 32% of its total land area dedicated to parks and recreational zones—an unusually high proportion compared to other African cities (Iwuagwu, 2022). These public spaces, including Millennium Park, Jabi Lake Park, and Central Park, present ideal locations for solar battery installations. Their vast open areas provide ample sunlight exposure, while their strategic locations within the city make them suitable for supporting the city's renewable energy needs. Furthermore, spaces like the National Children's Park and Zoo, as well as Maitama Amusement Park, could also be utilized to enhance Abuja's energy storage capabilities by integrating solar panels and

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battery systems into these green zones (GIZ, 2020).

In addition to public spaces, the rooftops of large commercial complexes, government offices, and institutions are also suitable for energy storage systems. Abuja's skyline, filled with modern office buildings and hotels, offers vast rooftop spaces that could be leveraged to install photovoltaic (PV) panels coupled with battery storage. A prime example of such initiatives is the University of Abuja's microgrid project, which features a 3.1 MWp solar PV system paired with 2.03 MWh of battery storage (EM-ONE Energy Solutions, 2022). This project is expected to generate over 5,000 MWh annually, providing valuable insights into the energy storage capacity that other commercial and governmental rooftops in the city could achieve. Scaling up such projects across rooftops in Central Business District, Wuse II, and Garki could greatly contribute to stabilizing the energy grid, particularly during peak hours, while promoting sustainable energy practices throughout the city (IRENA, 2021).

CONCLUSION

Abuja's urban landscape presents a promising avenue for integrating energy storage systems, particularly through the use of parks, public spaces, and rooftops of commercial and governmental buildings. These spaces offer the potential for solar battery installations, as demonstrated by projects like the University of Abuja's microgrid. Incorporating energy storage infrastructure into these urban elements not only improves energy reliability but also supports the city's transition to sustainable energy solutions, fostering long-term environmental and economic benefits for the growing capital. For further research, the integration of energy storage systems into Abuja's urban landscape can explore innovative ways to utilize both small and large-scale infrastructures. Detailed studies could assess the feasibility of retrofitting existing parks, public buildings, and commercial structures for solar energy installations. Additionally, examining the regulatory framework, public-private partnerships, and funding mechanisms for energy projects in Abuja will be essential. The environmental and social impacts of deploying renewable energy storage solutions in urban areas, particularly concerning public acceptance and city planning, should also be explored for comprehensive urban energy development strategies.

RECOMMENDATIONS

1. Maximizing Public Spaces for Renewable Infrastructure: Public parks, gardens, and recreational spaces like Millennium Park and Jabi Lake Park should be considered for large-scale solar energy storage systems. Their open layouts and access to sunlight make them ideal for deploying solar panels and battery storage.
2. Expanding Rooftop Installations: The government should encourage the installation of solar PV systems on the rooftops of commercial complexes, hotels, and government buildings, especially in dense business areas like Wuse II and Garki. Rooftop solar installations can reduce the load on the grid and serve as a backup during peak periods.
3. Incentivizing Energy Storage Projects: Policies and incentives should be introduced to encourage private and

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public sectors to invest in energy storage technologies across the city's urban elements. Tax credits or subsidies for building owners who incorporate renewable energy infrastructure can accelerate adoption.

4. Integrating Energy Storage in Future Urban Planning: Future urban development plans in Abuja should integrate energy storage systems into both new and existing structures, focusing on creating a resilient energy infrastructure that supports the city's growth and sustainability objectives.

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