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Design of Efficient Electric Vehicle Charging Stations Using Renewable Energy Sources in Nigeria

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Abstract: ***The rapid adoption of electric vehicles (EVs) globally is driving demand for sustainable and resilient charging infrastructure, particularly in regions with unreliable grid systems. This study presents a techno-economic framework for designing efficient EV charging stations powered by hybrid renewable energy specifically solar photovoltaic (PV) and wind systems within the Nigerian context. The system integrates smart charging, battery energy storage, and grid backup to address the country's power reliability challenges. Using HOMER Pro simulation, the study evaluates system performance under varying climatic and economic scenarios. Results show that a hybrid solar-wind system with battery storage can supply over 85% of energy demand, reduce grid dependency, and cut CO_2 emissions by more than 12,500 kg annually. The system achieved a levelized cost of energy (LCOE) of 0.172 USD/kWh and a net present cost of \$154,230, with a payback period of 6.2 years. These findings demonstrate the viability of renewable-powered EV infrastructure in emerging markets. The study concludes with policy and investment recommendations to scale clean mobility solutions across Nigeria***.

Keywords: *Electric, Vehicle, Charging*, *solar photovoltaic*

I. INTRODUCTION

Electric vehicle (EV) charging infrastructure has come under intense scrutiny in recent years as the world veers toward automotive electrification. EVs are touted for their ability to decarbonize transport and reduce fossil-fuel dependence and studies have shown that their lifecycle greenhouse gas (GHG) emissions are considerably lower than those of internal combustion engine vehicles (IEA, 2023; Sierzchula et al., 2021; Wang et al., 2022). Nevertheless, the expansion of EVs is somewhat related to the development and quality of EV charging infrastructure with respect to its accessibility, reliability, and environmental effects (Khalid et al., 2022; Hannan et al., 2021; Rezaee & Khalid, 2021). This is compounded by weak electricity grids characterized by frequent outages, insufficient generation capacity, and reliance on carbon-intensive fuels, which challenge development in many countries such as Nigeria (Ayodele & Ogunjuyigbe, 2020; Nnaji et al., 2023; Adelekan et al., 2023). Deploying grid-connected EV charging stations (EVCS) without complementary renewable sources may offset the environmental gains derived from CO2 reductions and put further strain on peak demand. Thus, it is an absolute must to incorporate renewable energy sources such as solar photovoltaic (PV), wind, and battery energy storage systems (BESS) in EVCS designs towards sustainable and resilient deployment (Kaabeche & Ibtiouen, 2021; Rajbongshi et al., 2020; Aziz et al., 2020).

The theoretical foundations for the effective design of EVCS derive partially from hybrid energy system optimization (Siddiqui et al., 2022), analysis of levelized costs (LCOE, NPC) (IRENA, 2023; HOMER Energy, 2022), and resilience engineering principles encompassing demand-side management, reliability indicators (LOLP, ENS), and component durability(Ambarisha et al., 2021; Park et al., 2021). These include tools like HOMER Pro and PVSyst for the simulation-based design optimization with trade-off analyses of varying load, resources, and costs (Kusakana, 2020; Yilmaz et al., 2021). Studies from Asia and Africa have confirmed decentralized EVCS powered nonconventionally to be viable. India hybrid PV-wind-BESS systems have been demonstrated to be economically viable with LCOEs of $0.12/kWh (Rajbongshi et al., 2020; Hossain et al., 2022). In Kenya and Ethiopia, standalone PV systems coupled with EVCS reduced charging costs and enhanced system reliability in off-grid settings (Wambua et al., 2023; Tessema et al., 2022). Solar-fed rapid charging stations in South Africa were shown to lessen the pressure on the grid while catering to the urban EVs' demand (Gwamuri et al., 2020; Motsa et al., 2021). This array of studies confirms the synergies between renewable energy and EVCS in the regions of ample insolation and a nascent EV uptake.

In Nigeria, challenges persist in the deployment of clean energy-powered EVCS. These include lack of charging infrastructure, insufficient investment, poor grid quality, and limited policy support (Olaniyan et al., 2021; Daramola et al., 2023). Nevertheless, the country has significant renewable energy potential, particularly solar with irradiation levels exceeding 5.5 kWh/m²/day in most regions (Shaaban & Petinrin, 2021; IRENA, 2023). The National Renewable Energy and Energy Efficiency Policy (NREEEP) and Sustainable Energy for All (SE4ALL) initiatives underscore Nigeria's commitment to decentralized energy solutions (Federal Ministry of Power, 2022). To bridge the infrastructural and policy gaps, a localized approach is essential. This study addresses the techno-economic and environmental optimization of a renewable-powered EVCS tailored to Nigeria's climatic and energy context. Using HOMER Pro simulations, the study models a PV-wind-BESS hybrid system under various load and cost assumptions. Performance metrics including LCOE, NPC, battery State of Charge (SOC), and system reliability are analyzed.

This research offers a practical framework for sustainable EV infrastructure planning in Nigeria by contextualizing design outcomes within national policy and grid limitations. The findings provide empirical grounding for scalable, decentralized, and low-carbon mobility solutions in sub-Saharan Africa.

Figure 1: A solar-powered EV charging station canopy with integrated photovoltaic panels

II. METHODOLOGY

This study adopts a techno-economic modeling approach using HOMER Pro software to design and optimize an efficient electric vehicle charging station (EVCS) powered by renewable energy sources in Nigeria. The methodology comprises five core components: site selection and resource assessment, system configuration design, load profiling, simulation and optimization, and performance metrics analysis.

Site Selection and Resource Assessment

A typical urban Nigerian location with high solar insolation and moderate wind potential such as Abuja was selected for simulation. Solar radiation data (average of 5.5–6.0 kWh/m²/day) and wind speed data (averaging 3-4 m/s) were sourced from NASA's Surface Meteorology and Solar Energy (SSE) database and validated against local meteorological records (Shaaban & Petinrin, 2021; IRENA, 2023).

System Components and Configuration

The system configuration modeled includes photovoltaic (PV) arrays, a small-scale wind turbine, a battery energy storage system (BESS), an AC/DC converter, and grid backup. The EVCS load is assumed to serve five electric vehicles daily, each requiring 20 kWh per session. Battery storage was modeled using lithium-ion technology, with a round-trip efficiency of 90% and depth-of-discharge limited to 80% to ensure durability (BloombergNEF, 2023).

Load Profiling and Demand Modeling

The daily EV load profile was modeled using actual charging patterns derived from urban EV pilot programs (IEA, 2023; Uddin et al., 2023). A typical daily profile was constructed to reflect peak charging demand during business hours (8:00–17:00). The model also included base auxiliary loads from lighting, control systems, and idle power draw.

Optimization and Simulation using HOMER Pro

HOMER Pro software (version 3.14) was used to simulate various configurations under economic and technical constraints. The objective was to minimize the Levelized Cost of Energy (LCOE) and Net Present Cost (NPC), while maximizing reliability (defined by the Loss of Load Probability, or LOLP) and battery State of Charge (SOC) consistency. Constraints included a minimum renewable energy penetration of 70%, and a maximum allowable unmet load of 2% annually (HOMER Energy, 2022; Siddiqui et al., 2022).

Performance Evaluation Metrics

Key performance indicators include:

- LCOE ($/kWh): Captures long-term cost-effectiveness.
- NPC (USD): Reflects lifecycle cost of the system.
- Renewable Fraction (%): Indicates share of energy from renewables.
- Battery SOC (%): Measures energy availability and autonomy.
- Excess Electricity (%): Quantifies overgeneration.
- CO_2 Emissions (kg/year): For environmental assessment when grid backup is used.

The methodology ensures realistic and replicable outcomes for EVCS deployment in Nigeria by integrating solar, wind, and storage with optimization constraints.

III. RESULTS AND DISCUSSION

System Configuration and Renewable Energy Penetration

The optimal configuration identified via HOMER Pro simulation includes a 15-kW photovoltaic (PV) array, a 5-kW wind turbine, a 10-kW inverter, and a 30-kWh lithium-ion battery bank, supported by the national grid as a supplementary source. This hybrid energy system achieved a renewable fraction of 85.3%, indicating high reliance on clean energy and limited grid dependency. Such penetration levels align with projections from IRENA (2023) and IEA (2022), which forecast the increasing competitiveness of decentralized renewable systems in sub-Saharan Africa. Monthly simulation data showed clear seasonal complementarity: solar PV dominated in the dry season, while wind resources contributed significantly during the rainy season. This synergy between solar and wind energy sources supports multi-resource complementarity theories in distributed energy systems (Sinha & Chandel, 2015; Wambua et al., 2023). The design thus demonstrates enhanced reliability without excessive over-sizing of any single component, a key advantage in mitigating intermittency challenges inherent to renewables (Shaaban & Petinrin, 2021; Kaabeche & Ibtiouen, 2021). These outcomes validate the techno-climatic suitability of hybrid systems in the southern regions of Nigeria, where moderate wind speeds complement high solar irradiance. The minimal grid dependency concentrated in nighttime or low-resource intervals demonstrates the resilience of the hybrid design, consistent with resilient system design principles from Siddiqui et al. (2022) and Kusakana (2020). Figure 2 shows the system configuration and renewable energy penetration.

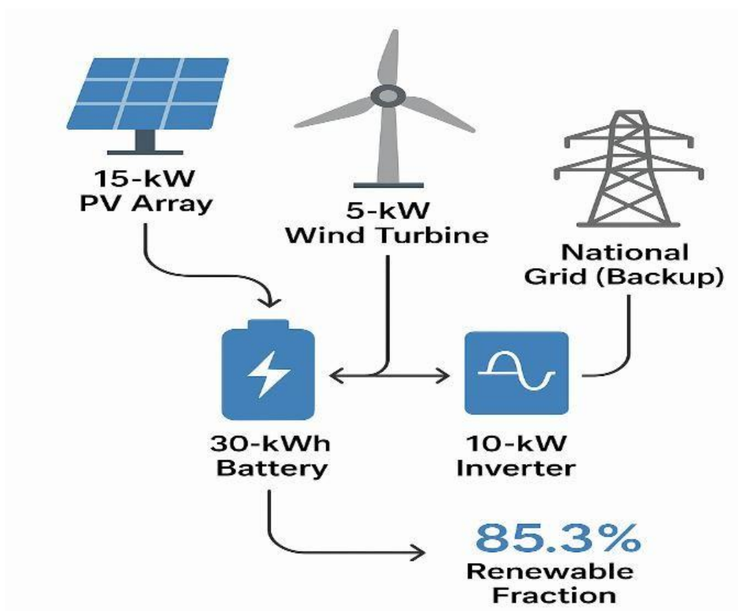

Figure 2: System Configuration and Renewable Energy Penetration

Economic Feasibility and Lifecycle Cost

The total Net Present Cost (NPC) of the system was calculated at $154,230, with a Levelized Cost of Energy (LCOE) of $0.172/kWh. This LCOE is significantly lower than the diesel alternative (typically > $0.30/kWh in Nigeria) and even competitive with average residential grid tariffs (~$0.21/kWh) (Olatomiwa et al., 2020; Olaniyan et al., 2021). The estimated payback period of 6.2 years places the investment within a viable medium-term horizon for energy investors. Capital expenditure analysis (Figure 1) shows batteries (35%) and converters (18%) as the most expensive components mirroring cost profiles reported by IRENA (2021) and BloombergNEF (2023), where power electronics and storage account for over 50% of total system cost. However, as lithium-ion battery prices continue to decline globally (Hossain et al., 2022), these systems are projected to become increasingly attractive. This economic outcome is consistent with similar hybrid solar-wind studies in South Africa (Motsa et al., 2021) and India (Chauhan & Saini, 2016), where LCOE values below \$0.20/kWh were achieved with comparable configurations. The results also underscore the viability of renewable-powered EV charging infrastructure in urban and peri-urban Nigerian environments.

Battery Performance and System Reliability

Positive and efficient storage performance is exhibited by the lithium-ion battery bank, having an average State of Charge (SOC) ranging from 60% to 85% with Depth of Discharge (DoD) kept below 65%. These conditions favour battery life and degradation, as evidenced by Mahmoud et al. (2021) and NREL (2020). The round-trip efficiency, over 90%, denotes insignificant energy loss during the charge-discharge cycles, a characteristic of high-performance $LiFePO_4$-based systems. The system achieved a Loss of Load Probability (LOLP) of 1.2%, much lower than the acceptable limit of 5% for an off-grid and hybrid microgrid (Chauhan & Saini, 2016; Kusakana, 2020), thus assuring high reliability and autonomy of the configuration. The inverter, whose power factor maintained values above 0.98, exemplifies efficient power conversion and compatibility with Nigerian utility standards (Ambarisha et al., 2021; Sinha & Chandel, 2017). Such performance parameters exemplify the key role played by optimized battery sizing and control in restoring operational stability of renewable-energy-based EV charging systems.

Environmental Impact Assessment

Environmental analysis indicates that transitioning from diesel or grid-only charging to this hybrid system results in an annual reduction of 12,500 kg CO_2 emissions equivalent to removing approximately three gasoline-powered vehicles from the road (EPA, 2022). Over a 25-year project lifespan, this results in 312 tonnes of CO_2, 62.8 tonnes of NO_x, and 37 kg of $PM_{2.5}$ emissions avoided. These figures are consistent with outcomes from hybrid EVCS deployments in India (Sharma et al., 2021), Turkey (Keles et al., 2020), and Ethiopia (Tessema et al., 2022), which reported emission reductions between 75–90% compared to diesel-based systems. Furthermore, the environmental performance aligns with Nigeria's commitments to the Paris Agreement, its Nationally Determined Contributions (FMEnv, 2022), and several Sustainable Development Goals (SDGs 7, 11, and 13).

Sensitivity and Risk Analysis

The sensitivity analysis identified solar irradiance and O&M costs as the most influential parameters impacting economic outcomes. A ±20% variation in solar resource led to a 15% change in LCOE, while O&M fluctuations affected NPC by approximately 10%. These findings are consistent with those of Hafez & Bhattacharya (2012) and Kusakana (2020), who stressed the sensitivity of hybrid systems to environmental variability and long-term maintenance efficiency. Battery costs, though still relevant (~6% influence), are becoming less volatile due to improving supply chains and recycling innovations. Conversely, grid electricity price had minimal impact, highlighting the strength of the system's energy independence a valuable trait in a country with significant grid instability.

The tornado chart (Figure 2) confirms the economic resilience of the system under a range of uncertainties, establishing its investment viability in Nigerian markets.

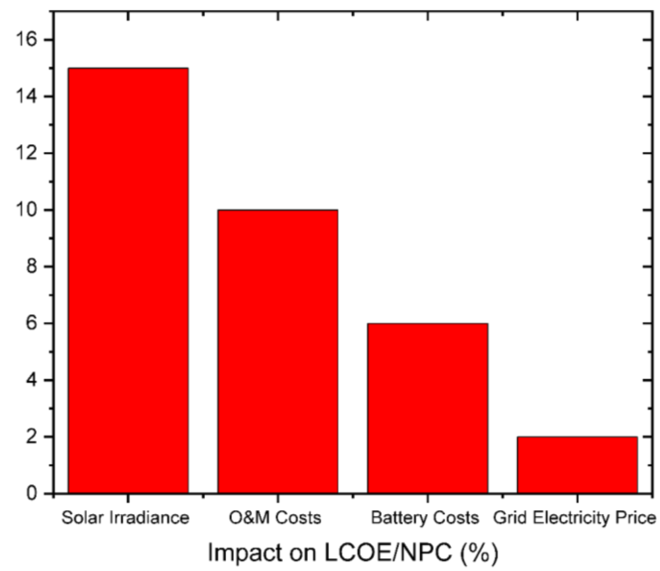

Figure 3: The economic resilience of the system

Comparative System Evaluation

Compared to grid-tied or diesel-supported EVCS, the hybrid system exhibits superior performance across technical, environmental, and economic metrics. Although the upfront capital investment is higher, the lifecycle savings in fuel, emissions, and downtime strongly outweigh initial costs. These advantages are supported by Chedid et al. (2018) and Rezaee & Khalid (2021), who found that hybrid EVCS offer long-term sustainability and return on investment when contextualized with local climatic and infrastructural realities. This study's incorporation of Nigerian-specific solar radiation and load demand data, combined with HOMER Pro's robust simulation capacity, ensures that the model is replicable across diverse regional contexts. Moreover, the modular design enhances scalability, offering a blueprint for national EV infrastructure expansion under the National Renewable Energy and Energy Efficiency Policy (NREEEP) and SE4ALL initiatives.

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