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(RESEARCH ARTICLE)

Optimal allocation of hybrid renewable energy sources for power system flexibility: A Case Study of Nigerian University

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Abstract

The increasing need for energy and environmental sustainability propels the use of renewable energy systems to mitigate greenhouse gas emissions and improve power supply flexibility. Efficient resource allocation is essential for sustaining a dependable distribution network. This paper examines the optimal incorporation of renewable energy resources into the power system of Ajayi Crowther University (ACU) to improve power supply flexibility and sustainability. By integrating hybrid renewable energy sources for distributed generation (HRESDG), including solar energy and battery energy storage systems, the university can markedly diminish its dependence on fossil fuels and their related environmental consequences. This study transforms the obstacles presented by the sporadic characteristics of renewable sources into possibilities, facilitating a more seamless transition to a sustainable energy mix. The study used an HRESDG optimization algorithm to strategically deploy renewable energy resources by identifying their ideal size, position, and timing within the campus power network. Historical sun irradiation data guided the creation of hybrid power models, while simulation research enhanced solar energy and battery storage designs. The results underscore the feasibility and advantages of renewable energy integration, providing essential information for policymakers and energy planners to develop flexible, economical, and sustainable power systems for university campuses. The study underscores the significance of uncertainty modeling and risk management to guarantee dependable and adaptable hybrid energy systems, establishing a solid framework for long-term sustainability.

Keywords: Optimal Allocation; Renewable Energy Sources; Power System Flexibility; Hybrid; University Campus.

1. Introduction

The strategic allocation of hybrid RES such as solar photovoltaic and battery energy storage within Ajayi Crowther University's power system represents a crucial research area. This focus is driven by advancing technologies, economic viability, environmental advantages, resource synergies, resource availability, and the growing capacity of these sources to meet the Ajayi Crowther University's high energy demands. Building upon prior studies on developing power models for renewable energy integration and the concept of flexibility in ACU's power system [1-3], this paper tackles the significant challenges posed by the determination of sizes and locations of these hybrid renewables in the Campus network. These challenges, compounded by the predominantly passive nature of current distribution network, hinder renewable energy integration. They particularly impact system operation and the incorporation capacity of renewable power into the power system. Leveraging distributed generations (DG) emerges a potent strategy for tackling the technical, economic, and ecological challenges in the power system. Moreover, it caters to the rising energy needs effectively [3]. DGs, as generating units, are strategically positioned within distribution systems, close to load centers, to meet immediate power needs. Their deployment aims to decrease on-peak operating expenses, postpone network enhancements, mitigate losses, improve power quality and reliability, decrease transmission and distribution (T&D)

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costs, relieve T&D load, diversify energy sources, and strengthen the power system while enhancing power stability [4-6]. Moreover, DGs, in contrast to centralized generations, are modular units that occupy limited landmass or area employing smaller generators, reduced capital costs and quicker building timeframes. The traditional distributed generation (DG) can either be connected to the grid or operate independently. DG systems display a wide range of dimensions and power capacities designed for certain applications and requirements. They range from single units as tiny as 1 kW to multi-unit setups capable of generating up to 300 MW. These systems are classified according to their power output: micro-scale DGs (1 kW - 5 kW), small-scale DGs (≥5 kW - 5 MW), medium-scale DGs (≥5 MW - 50 MW), and large-scale DGs (≥50 MW - 300 MW) [7]. Distributed generation may utilize renewable energy sources, non-renewable energy sources, or a combination of both. The hybrid characteristics of renewable energy-based distributed generators presents an attractive option, given their renewable and inexhaustible characteristics, synergy with other energy sources, environmental sustainability, technological readiness, and economic feasibility [2, 6]. Yet, the power output of HRESDGs like photovoltaic (PV) is highly variable [8, 9]. The variability arises due to factors such as weather conditions (solar). A system's ability to dynamically adjust its operating parameters in response to changing condition is its flexibility. Power system flexibility enables the power system to Promptly address fluctuations in the generation output of HRESDGs, facilitating the equilibrium of supply and demand while diminishing reliance on traditional backup power plants [10]. It facilitates the efficient use of renewable energy resources that are intrinsically intermittent and contingent upon variability factors. The integration of hybrid distributed generation (HRESDG), including solar photovoltaic (PV) systems and battery energy storages, into distribution networks is anticipated to rise in the coming years. This results from advantageous technology progress, economic viability, and environmental advantages [6]. The power system at Ajayi Crowther University, like many others, faces the challenge of integrating RES while maintaining system flexibility and reliability. Therefore, exploring solutions and strategies for integrating HRESDG units is crucial to ensure steady power supply and maximize renewable energy usage at the University. RE Hybrid Distributed Generators (HRESDGs) like solar PV, and battery energy storage offer a wide array of advantages beyond their environmental benefits. They provide low fuel costs, reduce greenhouse gas emissions, and contribute to energy security and independence. Additionally, they generate new job opportunities and drive economic growth in areas where they are implemented [6]. The integration of renewable energy DGs into the power system at Ajayi Crowther University faces challenges due to the variability and uncertainty of HRESDG resources and the passive setup of the network system. These challenges are further propelled by the lack of reactive power compensation in most renewable DG units. In addition, the variability of large-scale HRESDG power can lead to persistent system oscillations, requiring careful management for successful integration [4]. Suboptimal allocation or ineffective optimization of HRESDG units can escalate system oscillations and magnify the impact of intermittencies on HRESDG units within distribution network systems [11]. Therefore, strategically planning and designing the optimal allocation and timing of HRESDGs in the Ajayi Crowther University power system emerges as a viable methodology to address the intermittency issues. Notably, a significant portion of existing research in this domain has leveraged mixed-integer linear programming (MILP) for its diverse advantages [4, 12]. This study delved into the intricate optimization of where and how to place renewable DGs, factoring in voltage stability constraints for distributed generation planning. Its core objective was to reduce the net present value (NPV) of overall costs, which comprises financial investment, production, energy losses, maintenance, and unserved energy and focused on determining the ideal size and location for HRESDGs, considering transient stability constraints.

2. Materials and Methods

2.1. Site description for HRESDGs allocation

The site description for the allocation of HRESDGs at Ajayi Crowther University Campus focuses on identifying optimal locations for the integration of solar and battery storage systems. The selection process relies on data from the National Centre for Environmental Information (NCEI) and SolarGIS, ensuring that solar resources meet a minimum threshold of 1740.8 kWh/m^2/year. The integration strategy also takes into account the campus layout, including existing and planned generation sources, load pockets, available space, and potential for future energy generation. Located in Oyo Township, Nigeria, at coordinates 7.8496° N, 3.9480° E, the 0.51 km^2 campus serves a population of around 7,000, with an average annual electricity demand of 2.983 MWh, providing essential data for the efficient design of the renewable energy system.

2.2. Modeling of renewable energy resources of site under study

The modeling of renewable energy sources (RES) at Ajayi Crowther University involved analyzing five years of historical data on solar irradiance using various probability distribution functions, including Beta, Weibull, Gamma, and Log-normal. The data were divided into 3 seasons; raining season, dry season and harmattan season with each season containing 120 data points (5 years x 3 months x 30 days). MATLAB's "dfittool" was employed to fit the seasonal data is used to determine the shaping (a and k) and scaling (b and c) parameters for both the Beta and Weibull distributions. These parameters were then applied to transform the raw irradiance data. A one-year study period was chosen and broken down into typical days for each season, selected based on the lowest standard deviation from the 24-hour average irradiance. Each typical day was divided into 24 hourly segments, and the calculated parameters were used to generate frequency distributions for irradiance for each hour of the A typical day for each season. The Beta distribution functions were then derived for each hour, resulting in a total of 96 hourly periods across the year (24 hours per day, over four seasons).

2.3. Modeling of solar irradiance

Solar irradiance data for each hour of a typical day in every season generally exhibited two distinct distribution patterns. By analyzing these seasonal segments, we identified the parameters for the Beta probability density function (PDF). These parameters were subsequently used to characterize the hourly behavior of solar irradiance data for a typical day.

2.4. Modeling of solar PV and battery energy storage system power (MW)

2.4.1. Modeling of solar power output

The output power of the photovoltaic module in each state was affected by solar irradiation, site temperature, and the module's specifications. After creating the Beta PDF for a 24-hour period of a typical day, the PV module's output power during different states was calculated using its power performance curve for each hourly segment as done in [13].

2.4.2. Modeling of battery energy storage system power output

The output of the BESS unit is contingent upon the solar-PV production and the system's need. Modeling both the solar photovoltaic and battery energy storage system units enables the determination of their real production for the designated time period. A battery is the crucial component of a BESS as it stores electrical energy in the form of chemical energy. The BESS functions as a load during charging and as a generator during discharging. The BESS energy $E_{BESS}(t)$ time "t" was computed using Equation 1 and Equation 2.

$$E_{BESS}(t) = \begin{cases} E_{BESS}(t-1); & P_{diff}(t) = 0 \\ E_{BESS}(t-1) + P_{diff}(t) * \Delta t * \eta_{ch,}; & P_{diff}(t) < 0 \\ E_{BESS}(t-1) + \dfrac{P_{diff}(t)}{\eta_{disch}} * \Delta t; & P_{diff}(t) > 0 \end{cases} \quad \ldots (1)$$

$$P_{diff}(t) = P_{Load}(t) - P_{RDG}(t) \quad \ldots (2)$$

2.5. Mathematical representation of the planning issue

This section introduces a multi-stage optimization model aimed at identifying the ideal quantities, timings, and locations of HRESDGs, encompassing solar PV DGs and BESSs. The main goal of this model is to optimize the power generated and incorporated from HRESDGs into the Ajayi Crowther Power Distribution Network System (DNS) while reducing expenses. This model is formulated as a stochastic mixed-integer linear programming (MILP) optimization problem solved in a MATLAB environment. A linearized alternating current (AC) network model using fast decoupled power flow (FDPF) was utilized to accurately represent the features of the network system as done in [13].

2.5.1. The objective function

The objective of this planning formulation is to optimize the incorporation of renewable energy into the ACU Distribution Network System (DNS) from the standpoint of the Distribution System Operator (DSO). This entails the appropriate allocation of solar photovoltaic distributed generators and battery energy storage systems while minimizing expenses. The goal function of the established Mixed-Integer Linear Programming (MILP) optimization problem is to minimize the Net Present Value (NPV) of total costs, while adhering to the specified linear constraints.

$$C_T^{NPV} = \sum_{t\in\Omega^t} \frac{(1+d)^{-t}}{d} C_t^{I} + \sum_{t\in\Omega^t} (1+d)^{-t} (C_t^{M} + C_t^{E} + C_t^{X}) + \sum_{t\in\Omega^t} \frac{(1+d)^{-t}}{d} (C_T^{M} + C_T^{E} + C_T^{X}) \quad \ldots (3)$$

The first term in equation (3), the cost term C_t^{I} represents the total investment cost, amortized in annual installments over the lifespan of the installed components. This approach assumes reinvestment in identical components upon the expiration of their lifespan, as described by (Santos *et al.*, 2017) The cost valuation follows the concept of an unlimited or eternal planning horizon, as described in (Blank, 2017). This study calculates the total investment cost as the aggregate of the investment costs for both existing and new distributed generators (DGs) and battery banks. The second term in (3) pertains to the operational and welfare expenses over the temporal stages. This term comprises three cost components: total maintenance cost (${C_t}^M$), total energy cost (${C_t}^E$t), and total emission cost (${C_t}^X$). The maintenance cost, ${C_t}^M$, is the aggregate of the maintenance expenses for both current and new distributed generators (DGs) and battery banks at each planning phase, adhering to the notion of a continuous planning horizon. The cost term ${C_t}^E$ represents the total energy expenditure within the system, predicated on a continuous planning horizon. ${C_t}^E$ represents the aggregate costs of power produced by both existing and new distributed generators, as well as the procurement from the utility at each stage. The expenses associated with power generated by both existing and new distributed generators (DGs) are the product of the unit energy production cost (i.e., anticipated operational expenses) and the total power output. The cost term ${C_t}^X$ aggregates the emission costs related to both existing and new distributed generators, as well as the electricity from utility feeders. The emission cost refers to the anticipated expenses associated with emissions derived from the electricity generated by both existing and new distributed generators, as well as that procured from the utility. The emission cost function was considered to be linear for simplicity. Furthermore, the third term in equation (3) represents the net present value of the costs associated with production (maintenance and energy expenses) and emissions (welfare) following the final planning phase. This expense is also known as the terminal effect, considering the residual values of the invested assets. This term is calculated based on the concept of an indefinite planning horizon and is contingent upon the operational and emission costs of the final time stage.

The capital recovery factor $\frac{d(1+d)^{LT}}{(1+d)^{LT}-1}$ was used to amortize total investment expenses, ensuring a return on capital for each component. The specific capital recovery factors for different components were calculated as follows: for generators, $\frac{d(1+d)^{LT}g}{(1+d)^{LT}g-1}$ for all g ∈ DG; and for battery banks, $\frac{d(1+d)^{LT}cb}{(1+d)^{LT}cb-1}$ for all cb ∈ cb. Here, LT represents the lifetime of each component, and d represents the investment interest rate.

2.5.2. HRESDG allocation limitations

Constraints were imposed on the HRESDG allocation issue to limit the optimization of the objective function(s) while considering the choice variables. The limitations applied in the optimal HRESDG allocation problem formulation include power flow limitations, active and reactive power boundaries of HRESDG, voltage magnitude and angle constraints, reactive power limits of the battery bank, and active-reactive power balance [13].

2.6. Modeling of load demands

The hourly varying load demand of the test systems which in this case is Nigerian load profile was scaled with the Ajayi Crowther University Campus 10 bus network load demand profile. This was in line with some previous studies [12, 13].

2.7. **Capacity Utilization Factor**

The Capacity Utilization Factor (CUF) is a fundamental performance statistic used to analyze the efficiency and productivity of power generation systems, particularly in HRESDGs like solar and BESS. It is defined as the ratio of the actual output of a power plant for a certain duration to its potential maximum production had it functioned at full capacity during that time. CUF provides a clear measure of how effectively a power plant is being utilized. Higher CUF indicates better utilization and efficiency of the installed capacity.

The CUF is typically expressed as a percentage and is calculated using the following formula:

$$CUF = \frac{Actual\ Energy\ Output\ (KWh)}{Maximum\ possible\ Energy\ Output(KWh)} * 100$$

The natural variability of resources like sunlight greatly affects the CUF. For instance, solar power plants have a CUF ranging from 15% to 25%, depending on the location, technology used, and other factors.

3. Results and Discussions

The optimization in this study was based on data of June 2024, though the code is adaptable for other months or datasets from different periods. The simulation focused on the average daily load demand to better analyze the behavior of generators. A 10-bus system was investigated over a one-year planning period to test the developed model. Key assumptions and data for the optimization included a 2% maintenance cost for components, with the slack bus (Bus 1) set as the substation node with a voltage magnitude of 1.0pu and angle of 0.95pu. A 200 kWp solar DG capacity, determined using the capacity utilization factor, was considered as the potential DG power. The HRESDGs' penetration limit of 30%, exceeding Nigeria's 2030 renewable energy target, was applied. A 200kWh battery bank storage system, with a unit investment cost of N37,500/kWh, was included as the minimum deployable reactive compensator. The substation electricity price was set at N212/kWh, and the solar DG's cost was N127/kWh, with a power factor of 0.95 lagging, indicating the DGs absorb reactive power. The optimization was executed using MATLAB R2019a on an Intel(R) Core™ i3-10110U CPU at 2.10 GHz with 8 GB of RAM, and a stopping criterion of a 0.1% optimality gap was used.

3.1. **The ACU-10 bus location**

The drone view, showing the network data of the ACU-10 bus system in Ajayi Crowther is presented in Figure 1. This system has 10 load buses, which are located within specific locations at the university. This study makes use of the test system's temporal load demand (hourly load demand), which has been scaled in accordance with the real Ajayi Crowther load profile.

Figure 1 Aerial view of the Bus location

3.2. Findings from the Optimal REHDGS Allocation Analysis

Recurrent renewable energy production, such as photovoltaic-based distributed generators, typically operates with fixed lagging power factors, indicating a consistent draw of reactive power from the grid. Consequently, the power factor of the photovoltaic system in this study was 0.95. Recently, however, photovoltaic generator systems have been developed that can Offer reactive power support. However, the optimization of renewable energy distributed generators' integration into distribution networks in this study did not account for reactive power assistance from these systems. The optimization results are presented below. The computation time required to reach optimal solutions, based on the applied stopping criterion, was 18 seconds. The optimal solutions for solar PV and battery banks are presented in Tables 1.

Table 1 Optimal Investment Strategy for Solar Photovoltaic and Battery Storage Systems in Distribution System Planning.

S/NO	Bus	PVDGs	BESS
1	1	200kWp	200kWh
2	2	0	0
3	3	200kWp	200kWh
4	4	0	0
5	5	200kWp	200kWh
6	6	0	0
7	7	0	0
8	8	0	0
9	9	0	0
10	10	0	0

Table 1 reveals that solar DG units were installed equally on buses 1, 3, and 5, with no solar units installed on other buses, due to optimal roof orientation and tilt that enhanced the capacity utilization factor for solar PV at these locations. The total of 600 kWp of renewable power are installed in the network. The battery energy storage system (BESS) supplied supportive services, such as spinning reserves, to compensate for the intermittent nature of solar power. Table 1 also highlights that the optimal locations for battery banks were primarily on the loaded buses, as is typical in power system operations where batteries compensate for active power deficits, thus improving system flexibility and sustainability. The total installed battery capacity was 600 kWh. The results, depicted in Figures 2 and 3 show the complementarity between solar PV and battery storage, With the hybrid renewable generators strategically positioned in proximity, an optimality gap of 0.1% was attained. The incorporation of reactive compensators significantly enhanced the capacity of renewable distributed generation units by maintaining a balance between active and reactive power when generators that consume reactive power were utilized integrated into the system.

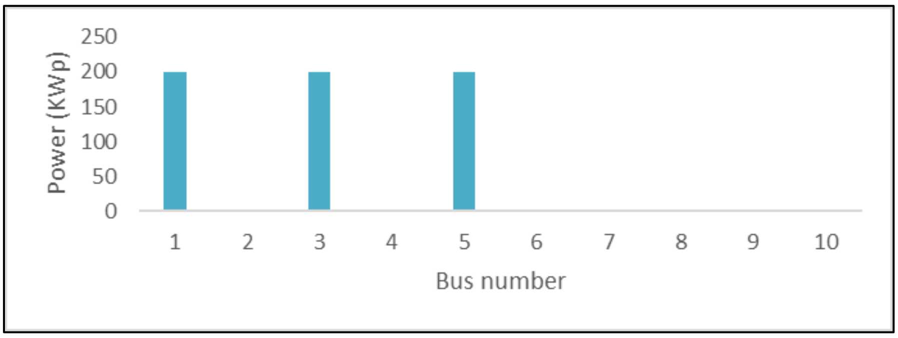

Figure 2 Optimal Sites and Capacities of Photovoltaic Power Installed Across the Planning Horizon

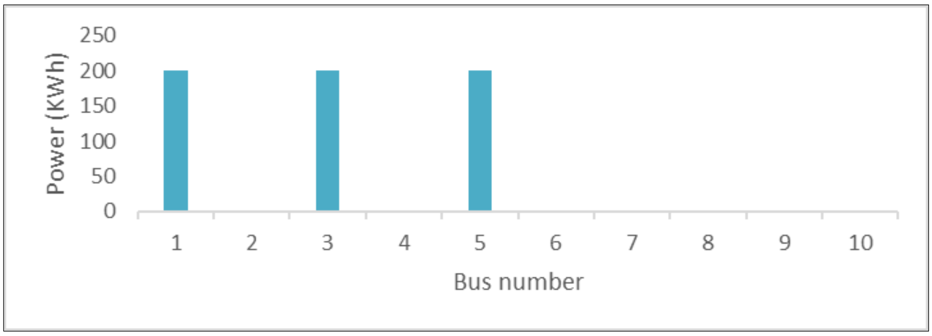

Figure 3 Optimal Capacities of Battery Energy Storage Systems Installed Across the Planning Horizon

For this particular study, ACU has an annual electricity demand of around 2.949 MWh, averaging 8,191.2kWh per day. Cost of electricity per kWh is 212 naira. Net cost in a year is N633.835 M. Adding the 600kWp PV parks and 600 kWh BESS reduced existing electricity bill by 73.6%, equivalent to the entire NPV investment costs of N714.295 M for the three planning stages. The cost of 600kWh BESS account for about 30% of the total cost of investment. The net present value (NPV) of maintenance, energy, and emission costs over the planning horizon amounted to N14.28 million, N67.41 million, and N574.221 million, respectively. The total NPV cost for all planning stages was N1.37 billion. By integrating a 600kWp and 600 kWh storage system within the HRESDG power setup, a total savings of N318.292 million would be achieved compared to relying solely on IBEDC's conventional power sources.

4. Conclusion

The optimal allocation of RES plays an essential function in augmenting the efficiency, reliability, and sustainability of power systems. By strategically placing and sizing renewable energy units within the Ajayi Crowther University (ACU) power system, this study successfully minimized power losses, reduced costs, and increased renewable energy utilization. The developed mathematical optimization model effectively accounted for the intermittency and variability of renewable energy sources, as well as investment costs, improving system reliability and cost-effectiveness. Key findings included a 73.8% reduction in ACU's yearly electricity bill, a 100% increase in power efficiency, a 65% increase in renewable energy utilization, and a 30% reduction in greenhouse gas emissions. The integration of solar and BSS demonstrated significant improvements in power system flexibility and sustainability, offering a reliable, cost-effective, and environmentally friendly energy solution for the University. Ongoing research and the incorporation of additional renewable resources are crucial for further enhancing system performance, adaptability, and long-term sustainability.

4.1. Recommendations

The study on the optimal allocation of hybrid renewable energy at Ajayi Crowther University (ACU) opens the foundation for future developments in sustainable energy systems. Future study should investigate the incorporation of supplementary RES, particularly biomass and wind, to diversify the energy mix and enhance system reliability. Wind power, in particular, can complement the existing photovoltaic (PV) systems by providing a more resilient energy supply. Detailed studies on wind patterns, turbine placements, and the integration of wind energy into the existing system are essential to maximize its potential. Furthermore, advancements in ES technologies, such as super capacitors, flywheels, and hydrogen storage, should be explored to improve energy management and system stability. These emerging technologies could provide alternative solutions to the current Battery Energy Storage Systems (BESS), ensuring a more reliable power supply. The application of advanced optimization techniques, such as machine learning and artificial intelligence, also presents an exciting avenue for improving system efficiency and accuracy. These techniques can analyze larger datasets, predict energy generation and consumption patterns, and optimize energy allocation strategies. Finally, fostering community engagement through educational programs and outreach initiatives can raise awareness about the benefits of renewable energy, creating a culture of sustainability and inspiring future generations to support and advance renewable energy solutions.

Compliance with ethical standards

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Disclosure of conflict of interest

The writers assert that they possess no conflicts of interest.

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