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INTEGRATED ASSESSMENT OF NUCLEAR-RENEWABLE HYBRID ENERGY SYSTEMS: A PATHWAY TO SUSTAINABLE AND RESILIENT INDUSTRIAL ELECTRIFICATION IN GHANA

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ABSTRACT

Purpose: Achieving sustainable and cost-effective industrial electrification in Africa necessitates an integrated energy approach that optimally combines Small Modular Reactor (SMR) and renewables, mainly solar and wind energy, as two clean energy sources.

Design/Methodology/Approach: Using HOMER Pro software, system performance was simulated to assess energy generation, economic viability, and environmental benefits. The analysis examined annual energy output, levelised cost of energy (LCOE), and carbon emission reductions to determine system sustainability.

Findings: Due to the integrated energy system, a net energy surplus of 206,079,408 kWh is achieved, enabling grid exports and the potential production of green hydrogen if effectively harnessed. Economic assessments indicate an LCOE of \$0.185/kWh, 34% lower than Ghana's industrial 2024 grid tariff. Additionally, CO_2 emissions are reduced by 15,824,965 kg annually, supporting Ghana's National Energy Transition Agenda.

Research Limitation: Further research is needed to optimise hybrid energy systems, particularly in waste management, policy frameworks, and national grid stability.

Practical Implication: SMRs and renewables can enhance energy reliability and affordability, ensure sustainable industrial development, and drastically lower energy sector emissions.

Social Implications: Integrating nuclear and renewable energy as a hybrid system can reduce energy poverty, drive industrial growth, support sustainable development, and lower environmental impact.

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Originality/Value: This study underscores the potential of nuclear-renewable hybrid energy systems to enhance energy security, reduce emissions, and stabilise industrial electricity supply.
Keywords: *Clean energy. climate change. energy access. mitigation. sustainable energy*

INTRODUCTION

Access to affordable, reliable, and sustainable electricity remains a cornerstone of socioeconomic development worldwide (UNDP, 2025). Thus, energy is indispensable for industrial growth, economic transformation, and improved living standards (IRENA & SELCO Foundation, 2022; Kaygusuz, 2009; The World Bank, 2022). However, a significant portion of the global population, particularly in Africa, still lacks reliable electricity, perpetuating cycles of underdevelopment, poverty, and social inequality (IEA, 2025; Murshed & Ozturk, 2023). Out of the world's electricity deficit, nearly 600 million Africans remain without electricity access, hindering industrialisation, economic growth, and the realisation of the Sustainable Development Goals (SDGs) (The World Bank, 2024).

Ghana's electricity demand is projected to rise significantly due to industrial expansion, particularly in mining and manufacturing (Ministry of Energy, 2021). Ghana's energy mix has traditionally depended on hydropower and thermal generation (Ghana Energy Commission, 2024a; Nyasapoh, 2018). However, these sources have proven inadequate due to climate-induced fluctuations in hydropower output and the high costs associated with thermal generation, which primarily relies on natural gas and imported fuels (Nyasapoh et al., 2022; Nyasapoh et al., 2023). Despite recent increases in installed electricity generation capacity to 5,639 MW in 2024, Ghana continues to face challenges such as fuel supply instability, rising tariffs, and an inadequate reserve margin (Ghana Energy Commission, 2024a). Moreover, the country's thermal power plants heavily depend on natural gas, exposing them to fuel supply risks and price volatility (Ghana Energy Commission, 2024b; Nyasapoh et al., 2022).

For the above reason, Ghana must explore alternative energy sources beyond conventional fossil fuel-based power generation to ensure a resilient and cost-effective power sector (Nyasapoh et al., 2024). Renewable energy, particularly solar and wind, has emerged as a viable option due to its declining costs and environmental benefits (Ministry of Energy, 2019; Nyasapoh et al., 2022). However, the intermittency and variability of renewables pose challenges to grid stability and reliability (Cosgrove et al., 2023; Nyasapoh et al., 2025; Nyasapoh, et al., 2022). Nuclear energy, on the other hand, offers a dependable, low-carbon baseload electricity supply, but concerns about safety, waste management, and capital costs have hindered its widespread adoption (Nuclear Energy Agency (NEA), 2020; Nyasapoh et al., 2024; Nyasapoh & Debrah, 2020).

A promising solution to these challenges is the integration of nuclear energy, specifically Small Modular Reactors (SMRs), with renewable sources in a hybrid energy system (IAEA, 2023a).

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Such integration optimally leverages the complementary strengths of nuclear and renewable (Esteves & Gabbar, 2023). Thus, nuclear energy provides a stable baseload, while renewables contribute variable but low-cost energy during peak periods (Gabbar & Abdussami, 2019; Ruth et al., 2014). This approach enhances grid resilience, minimises electricity costs, and reduces greenhouse gas emissions (Arefin et al., 2021). Consequently, the deployment of nuclear-renewable hybrid energy systems is particularly relevant for Ghana and other developing nations seeking a sustainable energy transition while addressing the limitations of their existing power infrastructure (Nyasapoh et al., 2024; Nyasapoh et al., 2024; Nyasapoh et al., 2023).

While significant progress has been made in deploying nuclear-renewable hybrid energy systems globally, research on their applicability in Ghana's industrial energy landscape remains limited. Existing studies have examined mainly nuclear and renewable energy in isolation rather than as complementary technologies in a hybrid system. Hence, there is a pressing need for a comprehensive integrated assessment of nuclear-renewable hybrid energy systems in the context of sustainable economic growth and development in Ghana. The synergy between nuclear and renewable energy sources fosters a sustainable energy transition. Nuclear power ensures reliability, while renewables contribute to cost-effectiveness and environmental sustainability (NREL, 2020). The nuclear and renewable hybrid energy systems support energy independence, reduce reliance on imported fossil fuels, and stimulate economic growth through job creation and technological innovation (IAEA, 2023b).

This study fills this gap by analysing the feasibility and economic viability of an SMR-renewable, mainly solar and wind hybrid energy system tailored for industrial applications, such as mining in Ghana. The urgency of this study is underscored by Ghana's increasing electricity demand and the pressing need to transition to a sustainable and cost-effective energy model. The study evaluates Nuclear-Renewable Hybrid Energy Systems as a Pathway to Sustainable and Resilient Industrial Electrification in Ghana. The study employed HOMER Pro software to simulate and optimise the hybrid energy configurations using energy dispatch and cost parameters.

By addressing the gaps in existing literature and presenting a holistic analysis of nuclear-renewable hybrid energy systems, this study contributes significantly to the discourse on sustainable energy transitions. It provides empirical insights for policymakers, energy planners, and investors on integrating SMRs and renewables into Ghana's power sector. The findings will inform strategies to enhance energy resilience, reduce costs, and support industrial electrification, serving as a model for other developing countries facing similar energy challenges. The study includes an introduction and a brief overview of integrated nuclear-renewable hybrid energy systems. The study then presents its methodology, results, and discussions, concluding with key recommendations for policymakers and industry stakeholders.

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INTEGRATED NUCLEAR-RENEWABLE HYBRID ENERGY SYSTEMS

Integrating nuclear and renewable energy sources in hybrid energy systems presents a transformative approach to enhancing the efficiency, reliability, and affordability of clean energy generation (Arefin et al., 2021; Gabbar & Abdussami, 2019; IAEA, 2023b). By leveraging the complementary strengths of nuclear and intermittent renewable energy sources such as solar and wind, these systems mitigate energy supply challenges while promoting sustainability (Ruth et al., 2014).

Nuclear energy serves as a stable baseload power source, while solar and wind energy contribute intermittent but essential additions to the power mix (Esteves & Gabbar, 2023; Nyasapoh et al., 2022). The hybridisation of nuclear and renewable energy technologies optimises electricity production, reduces greenhouse gas emissions, and minimises dependency on fossil fuels (IAEA, 2023). Additionally, the integration of storage systems such as batteries enables surplus energy generated by renewables to be stored and dispatched when needed, and this can enhance grid stability (Cosgrove et al., 2023; Tan et al., 2021). Figure 1 provides a conceptual framework illustrating how nuclear power and renewable energy sources interact to ensure a stable and resilient electricity supply.

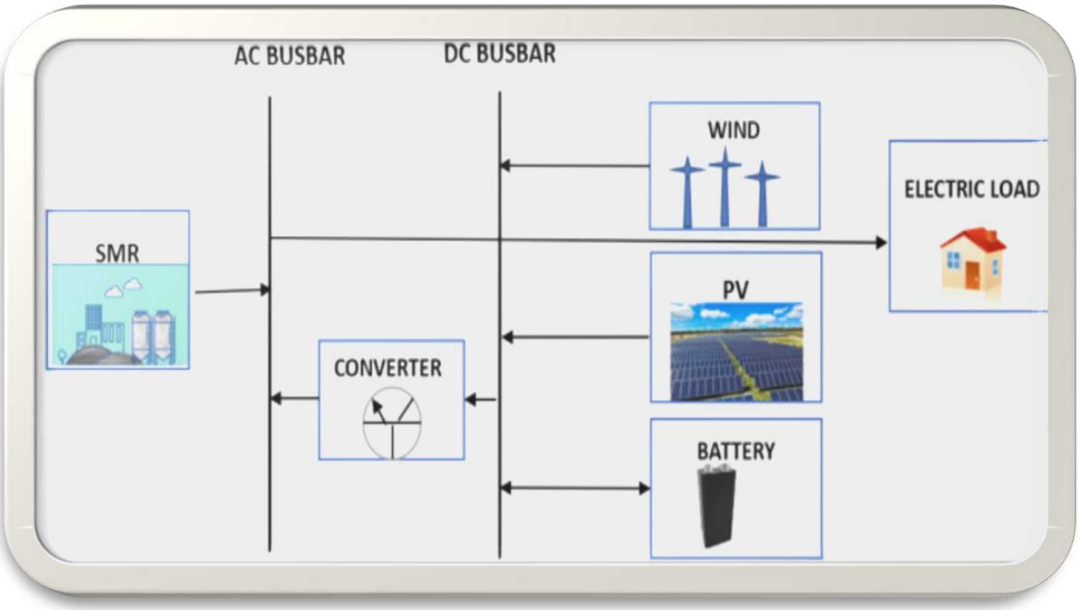

Figure 1: Conceptual Framework for "Nuclear and Renewable Hybrid Energy Systems" (Source: Authors' draft)

The conceptual framework of the nuclear-renewable energy system highlights the energy flow for sustainable power generation. The integrated system has been designed so that the power generated from solar and wind sources is initially produced as direct current (DC). This power is stored in batteries for future use or converted into alternating current (AC) and supplied to the electrical grid. Meanwhile, Small Modular Reactors (SMRs) provide a continuous and

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stable AC output, ensuring that energy demand is consistently met. This integrated approach mitigates the intermittency challenges of solar and wind energy, creating a more resilient and sustainable power system (Esteves & Gabbar, 2023).

Nuclear-Renewable Hybrid Systems for Grid Stability and Industrial Electrification

Nuclear power forms the backbone of hybrid energy systems by providing a consistent baseload supply at all times when needed (Debrah et al., 2020; Jenkins et al., 2018). While intermittent renewables are subject to environmental variability, nuclear energy remains unaffected by weather conditions, ensuring an uninterrupted power supply (World Nuclear Association, 2022). A very critical role of solar and wind energy, despite their intermittent nature, is the crucial role of helping to meet peak load, thereby reducing dependency on fossil fuel-based peaking plants (Liou, 2021). Fig. 2 illustrates the capacity factors of different energy sources, highlighting nuclear energy as the most reliable power source. Thus, in 2021, nuclear energy operated at a capacity factor exceeding 92%, significantly higher than any other energy source for power generation (US Department of Energy, 2020). Hence, the reliability of nuclear energy makes the power source a critical component of hybrid energy systems, ensuring consistent electricity generation with intermittent energy sources such as solar and wind (Loisel et al., 2018).

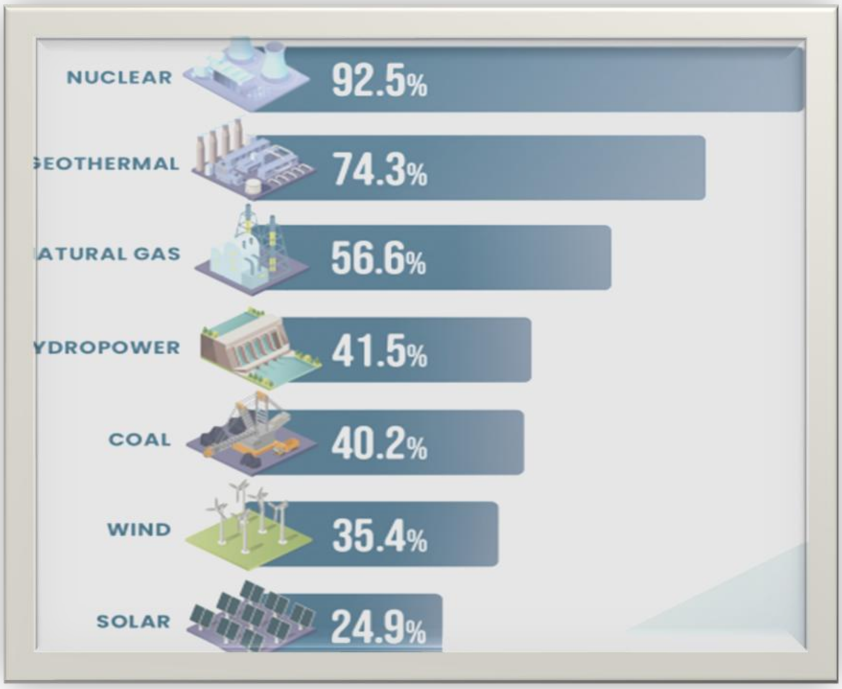

Figure 2: Capacity Factor for each type of energy (US Department of Energy, 2020).

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Consequently, as a result of the leverage of the high-capacity factor of nuclear power and the cost-effectiveness of renewables, hybrid systems can offer an optimal solution for sustainable and resilient industrial electrification in Ghana (Nyasapoh et al., 2024). The integration of nuclear and intermittent renewable technologies enhances grid stability, reduces electricity costs, and ensures energy security (Esteves & Gabbar, 2023).

Notably, one of the primary challenges of renewable energy, such as solar and wind deployment, is intermittency (Cosgrove et al., 2023). For instance, solar power generation varies with daylight availability, while wind power depends on fluctuating wind speeds (Nyasapoh et al., 2025; The Economist, 2022). However, the emergence of hybrid energy systems overcomes the challenges of intermittency through the integration of steady nuclear power with intelligent grid management and energy storage solutions (IAEA, 2023b). Thus, during periods of low solar and wind generation, nuclear power ensures a continuous supply of electricity, preventing grid instability and power shortages (Jenkins et al., 2018). Also, advanced grid management techniques, such as demand-response strategies and battery storage integration, further enhance the system's resilience (Rahman & Zhang, 2023). Employing balancing renewable intermittency with nuclear baseload generation, the hybrid energy system provides a stable and sustainable energy supply tailored to Ghana's industrial and economic growth needs (Gabbar et al., 2020; Nyasapoh et al., 2022).

Adopting nuclear-renewable hybrid systems aligns with Ghana's energy transition goals to ensure a sustainable, resilient, and cost-effective electricity supply (Ministry of Energy, 2023). Hence, Ghana can position itself as a leader in sustainable energy innovation while addressing critical electricity demand challenges by designing and successfully implementing nuclear-renewable hybrid energy systems. This approach presents a viable pathway to achieving industrial electrification and long-term energy sustainability.

METHODOLOGY

This study employs HOMER Pro software, a robust and widely recognised energy modelling tool, to simulate and optimise the proposed nuclear-renewable hybrid energy system for industrial applications in Ghana. The methodology integrates technical, economic, and environmental analyses, ensuring a comprehensive assessment of the system's feasibility and performance (HOMER Energy, 2023). HOMER Pro enables the evaluation of energy dispatch strategies, system configurations, cost implications, and environmental impact, allowing for an optimal design that meets the energy demands of industrial consumers while ensuring sustainability and economic viability.

Nuclear Renewable Hybrid Energy System Generation Modelling

The simulation begins with modelling each component's energy generation, including Small Modular Reactor (SMR), solar photovoltaic (PV) system, wind turbine, and lithium-ion battery storage, to determine the total annual electricity output.

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The total power output of the hybrid energy system at any time *t* is expressed in the model as seen in Equation 1.

$$P_{total}(t) = P_{SMR}(t) + P_{solar}(t) + P_{wind}(t) + P_{battery}(t) - P_{load}(t) \qquad (1)$$

Where;

$P_{total}(t)$: total power available at time t.
$P_{SMR}(t)$: power contribution from the Small Modular Reactor (SMR).
$P_{solar}(t)$: solar PV generation varies based on solar irradiation.
$P_{wind}(t)$: power output from wind turbines, dependent on wind speeds.
$P_{battery}(t)$: the charging and discharging of the lithium-ion battery.
$P_{load}(t)$: total electricity demand of the mining community.

Small Modular Reactor (SMR) Power Output Calculation

In the hybrid energy system, the Small Modular Reactor (SMR) operates as a genset, acting as a baseload energy source. Equation 2 represents the power output of the SMR as modeled, in addition to the capacity factor and fuel consumption rate as seen in Equations 3 and 4.

$$P_{SMR} = C_{SMR} \times CF_{SMR} \qquad (2)$$

Where:

P_{SMR} : actual power output of the SMR (kw).
C_{SMR} : installed capacity of the SMR (kw).
CF_{SMR} : the capacity factor, representing the fraction of the reactor's time at full load.

The capacity factor of the SMR is calculated as:

$$CF_{SMR} = \frac{E_{actual}}{E_{max}} \qquad (3)$$

Where:

E_{actual} : actual annual energy output of the SMR (kWh).
E_{max} : maximum possible annual energy generation assuming continuous full-load operation (kwh).

The fuel consumption rate for the SMR is determined as:

$$F_{SMR} = \frac{P_{SMR}}{\eta_{SMR}} \qquad (4)$$

Where:

F_{SMR} : fuel consumption rate (kg or liters per hour).

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η_{SMR} : thermal efficiency of the SMR.

The SMR operates continuously, ensuring a stable and reliable power supply for industrial operations, particularly in scenarios of low solar irradiation and wind availability.

Solar PV Power Output Calculation

Equation 5 presents the power output of the solar PV system as used by the model for the simulation analysis and optimisation.

$$P_{solar} = A \times G \times \eta_{PV} \quad (5)$$

Where:

A : total solar panel area (m^2).
G : solar irradiance (kW/m^2).
η_{PV} : efficiency of the solar PV system.

Wind Power Output Calculation

The wind turbine's power output is calculated using Equation 6 for the needed simulation analysis in the model.

$$P_{wind} = \frac{1}{2} \rho A v^3 C_P \quad (6)$$

Where:

ρ : air density (kg/m^3).
A : swept area of the turbine blades (m^2).
v : wind speed (m/s).
C_p : power coefficient of the wind turbine.

Battery Storage Operation

The state of charge (SOC) of the lithium-ion (LI) battery is modelled, and the model uses the calculation in Equation 7.

$$SOC(t) = SOC(t - 1) + \frac{P_{charge\,(t)} - P_{discharge\,(t)}}{C_{battery}} \times \eta_{battery} \quad (7)$$

Where:

SOC (t) : state of charge at time t.
$P_{charge}(t)$: power used to charge the battery.
$P_{discharge}(t)$: power drawn from the battery.
$C_{battery}$: battery capacity (kWh).
$\eta_{battery}$: charging/discharging efficiency.

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Economic Viability Assessment

The hybrid system's economic viability is assessed through a detailed financial analysis, which includes calculations of the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), Return on Investment (ROI), and Payback Period. These economic indicators provide insights into the nuclear renewable hybrid energy system's affordability and long-term financial sustainability.

Levelized Cost of Energy (LCOE)

The LCOE is a key economic indicator that determines the cost of energy production over the system's lifetime and is given by the representation in Equation 8.

$$\text{LCOE} = \frac{\Sigma\,(Ccapital + Coperation + Cmaintenance + Cfuel)}{\Sigma\,Egenerated} \qquad (8)$$

Where:

- C_{capital} : total capital cost of the hybrid system.
- $C_{\text{operation}}$: annual operational costs.
- $C_{\text{maintenance}}$: maintenance cost over the system's lifetime.
- C_{fuel} : includes fuel costs, particularly for the SMR.
- $E_{\text{generated}}$: total energy generated over the system's lifetime.

Net Present Cost (NPC)

The Net Present Cost (NPC) evaluates the total cost of the hybrid energy system over the project's operational lifetime. It is calculated in the model as represented in Equation 9.

$$\text{NPC} = \sum_{t=0}^{N} \frac{c_t}{(1+r)^t} \qquad (9)$$

Where:

- C_t : total cost incurred in year t.
- r : discount rate.
- N : project lifetime (years).

Return on Investment (ROI) and Payback Period

While the ROI assesses the system's profitability, the payback period (PP) helps determine the time required for the project to recover its initial investment. The calculations of the ROI and Payback Period are represented in Equations 10 and 11.

$$\text{ROI} = \frac{Net\ Profit}{Total\ Investment} \times 100 \qquad (10)$$

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$$PP = \frac{C_{capital}}{Annual\ Savings} \qquad (11)$$

Where:

Annual savings refer to the cost savings compared to conventional energy sources.

Environmental Impact Assessment

The environmental impact of the nuclear renewable hybrid energy system is evaluated by quantifying CO_2 emission reductions compared to conventional fossil-fuel-based energy systems. The calculation of the total CO_2 emissions avoided in the model is represented in Equation 12.

$$E_{CO2} = E_{grid} \times EF_{grid} \qquad (12)$$

Where:

E_{CO2} :total CO_2 emissions reduced (kg).
E_{grid} : energy offset from fossil-fuel-based grid power (kWh).
EF_{grid} : grid emission factor (kg CO_2/kWh).

Key parameters and constraints were carefully defined within HOMER Pro to ensure realistic and precise modelling. The system components and configurations were selected based on energy demand projections, resource availability, and cost considerations, ensuring that the hybrid system is optimised for efficiency, reliability, and sustainability.

System Components and Configuration

About the Conceptual Framework for the Nuclear and Renewables (Solar and Wind) Hybrid Energy System in Fig. 1, the proposed energy supply system is designed for a mining community in Ghana. It integrates 70% Small Modular Reactor (SMR) power and 30% renewable energy sources, comprising solar PV and wind energy. A lithium-ion battery storage system has been incorporated to enhance system reliability and mitigate the intermittency challenges associated with renewable energy sources.

Figure 3 presents a schematic representation of the hybrid energy system, highlighting the interconnected grid, electric load, SMR, solar PV, wind farm, and battery storage. The system configuration allows optimal energy dispatch, ensuring a reliable, cost-effective, and sustainable electricity supply for industrial applications.

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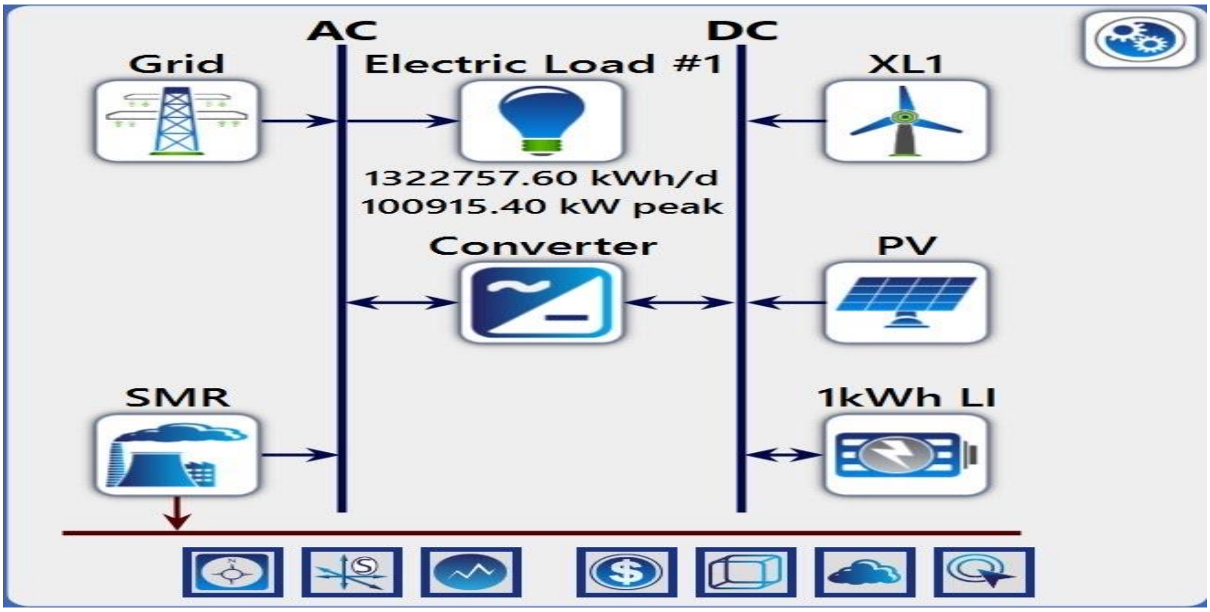

Figure 3: Schematic representation of the hybrid energy system

The Small Modular Reactor (SMR) serves as the baseload power source, ensuring a stable and continuous supply of electricity to meet the high energy demands of industrial operations. The selected SMR has a nominal capacity of 60,000 kW, offering a dependable power backbone for the hybrid system. The solar photovoltaic (PV) system plays a crucial role in the hybrid configuration, leveraging Ghana's high solar irradiation levels to enhance energy generation. The system has a nominal installed capacity of 161,114 kW, contributing a substantial share to the hybrid energy mix. The wind farm (XLI), though a minor contributor relative to nuclear and solar, provides additional energy when wind conditions are favourable, thereby increasing system diversification and resilience. The installed wind capacity is 2,019 kW, which supplements the hybrid system during peak wind availability. To address the intermittency of renewable energy sources, the system incorporates a lithium-ion (LI) battery storage unit with a nominal capacity of 157,201 kWh. This storage unit ensures grid stability by storing excess renewable energy during peak generation periods and discharging when solar and wind generation are insufficient.

The Hybrid Energy Systems

The hybrid energy system for this study is designed to integrate with the national grid in both the current and proposed configurations. This strategic approach ensures a stable and continuous power supply to the mining community while enabling surplus energy exchange between the hybrid system and the grid. Interacting dynamically with the grid enhances grid stability, energy security, and economic viability, ensuring reliable electricity availability for industrial applications.

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Current Hybrid Energy System

The current hybrid energy system comprises solar photovoltaic (PV) generation, a Small Modular Reactor (SMR) operating as a baseload power source, and the grid connection. In this configuration, wind power and battery storage are not included, making the system partially dependent on grid support for balancing demand and supply fluctuations. The SMR is the primary energy source, providing baseload power, while solar PV contributes supplementary energy generation during the day. However, due to the absence of battery storage and wind energy, the system may experience variability challenges, requiring occasional reliance on grid electricity for balancing.

While partially sustainable, this configuration lacks the flexibility to optimise renewable energy penetration and ensure long-term resilience. The absence of battery storage limits the system's ability to store excess solar energy, and excluding wind power reduces opportunities for diversified renewable energy generation. Figure 4 illustrates the structure of the current hybrid energy system.

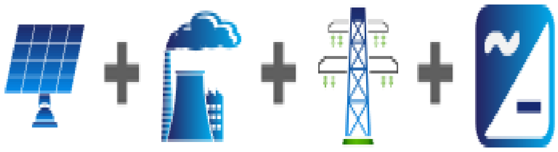

Figure 4: Current hybrid energy system

Proposed Hybrid Energy System

The proposed hybrid energy system represents an optimised configuration that enhances renewable energy integration, energy storage, and system resilience. This improved system comprises solar PV, wind energy, a Small Modular Reactor (SMR), and lithium-ion battery storage, ensuring a diversified and well-balanced energy mix. Adding wind energy and battery storage significantly improves the system's ability to store excess energy, mitigate intermittency, and enhance grid stability. The proposed hybrid system maximises the use of renewable energy while maintaining system reliability through SMR baseload generation and battery storage. The ability to store excess renewable energy and export surplus electricity to the grid further enhances its economic and operational feasibility. Figure 5 provides a representation of the proposed nuclear-renewable hybrid energy system.

Figure 5: Current Hybrid Energy System

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Simulation Approach and Optimisation Process

The simulation follows a chronological optimisation strategy, where hourly energy demand and supply profiles are analysed over a full-year operational period. As defined, the HOMER Pro performs sensitivity analyses to assess the system's performance under varying resource availability, cost fluctuations, and policy scenarios. Key output parameters include total energy generation, technology generational fraction, system reliability, economic savings, and emissions reductions. The model ensures that grid interaction is accounted for, with net energy exports per year, presenting opportunities for grid integration and green hydrogen production. The economic analysis with multiple financial metrics provides a holistic financial evaluation of the hybrid system.

Source of Data

The data on Solar, Wind and Battery Storage was sourced in HOMER Pro Software to suit the study's location and parameters (HOMER Energy, 2023).

Solar Resource Data

The solar resource data used in HOMER Pro for this study was obtained from NASA's Surface Meteorology and Solar Energy Database and other publicly available meteorological datasets, such as the National Renewable Energy Laboratory (NREL) and Global Solar Atlas (World Bank Group, 2024a). The data was imported into HOMER Pro to ensure an accurate representation of solar irradiance levels in the study region (HOMER Energy, 2023).

Wind Resource Data

The wind resource data for the study was sourced from the Global Wind Atlas (GWA), NASA, and on-site meteorological stations (World Bank Group, 2024b). HOMER Pro requires wind speed data at a specific height to simulate wind energy potential (HOMER Energy, 2023).

Battery Storage Data

The lithium-ion battery storage system was modeled in HOMER Pro to store excess energy from solar and wind power generation. The storage system ensures grid stability and reliability by providing backup power during low renewable energy production periods (HOMER Energy, 2023).

Electricity Demand Data and SMR Data

The electricity demand data for the mining community was obtained from the Energy Commission of Ghana. However, due to confidentiality concerns, the specific details of the data cannot be disclosed. The data on Small Modular Reactors (SMRs) used in this study is primarily obtained from the International Atomic Energy Agency (IAEA) data repository (IAEA, 2025b, 2025a).

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RESULTS AND DISCUSSION

Analysing the nuclear-renewable hybrid energy system provides crucial insights into its performance, economic viability, environmental impact, and grid interactions. The study evaluates the feasibility of integrating Small Modular Reactors (SMRs) with renewable energy sources such as solar and wind in Ghana's industrial sector. The results demonstrate that the hybrid system presents an efficient and sustainable pathway for industrial electrification, particularly in energy-intensive sectors like mining. The discussion is structured into five key areas: energy generation performance, economic assessment, environmental benefits, grid interaction, and a comparative evaluation against Ghana's conventional fossil fuel-based power systems.

Energy Generation Performance

The hybrid energy system under study ensures a stable and continuous electricity supply, which is crucial for industrial operations such as mining, where energy reliability is a key factor in maintaining productivity. The study's output revealed that the microgrid of the hybrid energy system requires 1,888,776 kWh/day**,** with a peak power demand of 159,124 kW**.** Fig. 6 shows the electricity production with the share of the technology options modelled in the hybrid energy system. To achieve this energy supply, the hybrid system integrates a 60,000 kW Small Modular Reactor (SMR), a 161,114-kW solar photovoltaic (PV) system, and a 2,019-kW wind power system**,** creating a well-balanced mix between nuclear baseload power and intermittent renewable energy sources. The SMR serves as the primary baseload power provider, producing 457,066,592 kWh annually**,** ensuring energy stability while mitigating solar and wind generation fluctuations.

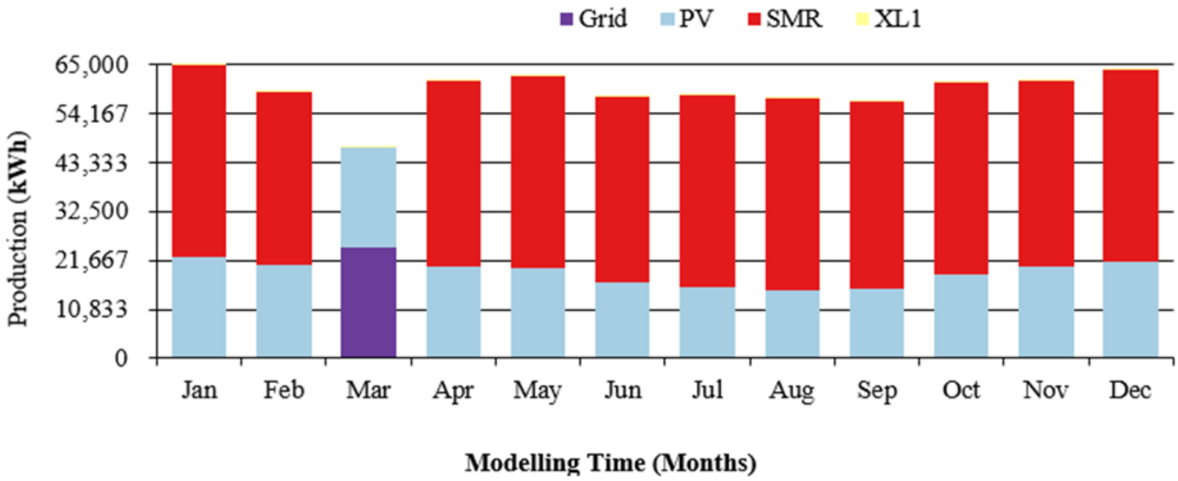

Figure 6: Electricity Generation

The solar PV system, with a nominal capacity of 161,114 kW, contributes 227,992,352 kWh annually**,** accounting for 47.2% of the total energy mix. The wind energy system, rated at 2,019 kW**,** generates 1,147,001 kWh annually, representing only 0.238% of the total power supply due to regional wind limitations. To address the intermittency associated with solar and wind

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energy, a lithium-ion battery storage system with a nominal capacity of 157,201 kWh is integrated, storing 22,437,698 kWh per year and providing 2.28 hours of autonomy.

For this study, the hybrid system achieves a 30% renewable energy penetration, significantly reducing dependence on fossil fuels while aligning with Ghana's National Energy Transition agenda (Ministry of Energy, 2023) and international decarbonisation goals (MESTI, 2021). By integrating nuclear energy with renewables, the system ensures a continuous, low-carbon electricity supply, which is essential for industrial growth and economic competitiveness, as evidenced in several studies (Adelekan et al., 2024; Brook et al., 2014; Nyasapoh et al., 2022).

Additionally, several other studies confirm the advantages of nuclear-renewable hybrid systems in ensuring energy security and cost efficiency. Zhang (2023) emphasises that hybrid nuclear-renewable systems minimise reliance on fossil fuels while enhancing industrial energy resilience. Similarly, Huang et al. (2023) highlight that combining SMRs with renewables improves load-following capabilities, making these systems highly suitable for industrial-scale operations. Additionally, IAEA (2023c, 2023b) asserted that nuclear-renewable energy systems support sustainable energy transitions by reducing grid dependence and greenhouse gas emissions.

Moreover, Brook et al. (2014) argue that while renewables play a crucial role in sustainable energy development, their inherent intermittency requires a stable backup source, which is often fossil-fuel-based. They contend that nuclear energy is the only fully developed low-carbon energy source capable of delivering the large-scale, consistent power required to meet modern industrial demands. Their research further demonstrates that nuclear fission technology, particularly SMRs, can significantly reduce greenhouse gas emissions and enhance grid stability, making it an indispensable component of a future clean energy system. This perspective reinforces the significance of integrating nuclear power with renewables to ensure grid reliability, particularly in countries like Ghana that seek to decarbonise their energy mix while maintaining industrial growth.

Nuclear-renewable hybrid systems are gaining traction as a viable decarbonisation and industrial electrification solution. The International Energy Agency (IEA, 2025) recognises China and India as frontrunners in adopting these systems, driven by the need for energy diversification and carbon reduction. Ghana's decision to integrate a hybrid SMR-renewable system positions the country as a leader in Africa's clean energy transition, setting a precedent for other developing nations to follow.

Economic Assessment of the Integrated Hybrid System

The economic viability of the nuclear-renewable hybrid energy system is assessed based on critical financial indicators, including the Levelized Cost of Energy (LCOE), Net Present Cost (NPC), payback period, Return on Investment (ROI), and the Internal Rate of Return (IRR). The study reveals that the LCOE of the system is $0.1846/kWh, which represents a 34%

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reduction compared to Ghana's 2024 grid tariff of $0.2804/kWh, making it an economically competitive alternative for industrial applications. Figure 7 represents the LCOE Comparison, Cost Breakdown, and Investment Payback Timeline for the nuclear-renewable hybrid energy system study.

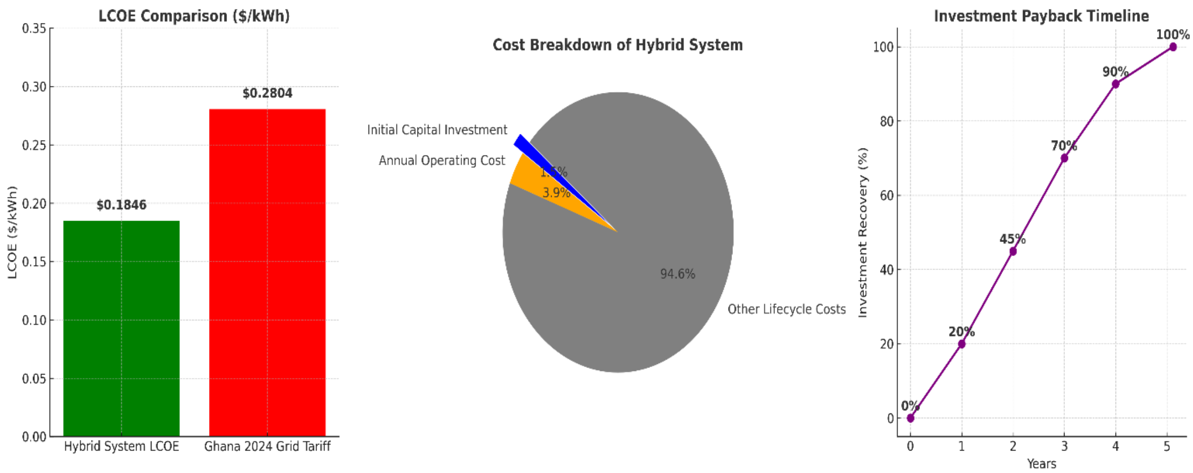

Figure 7: LCOE Comparison, Cost Breakdown, and Investment Payback Timeline

The system's Total Net Present Cost (NPC) is estimated at $1.60 billion, accounting for capital, operational, and maintenance expenses throughout the system's lifecycle. The initial capital investment required for the project is $24.8 million, with an annual operating cost of $61.77 million. The system exhibits strong financial viability, with a payback period of 5.12 years, meaning that the investment cost is recovered within this period through energy savings and revenue generation.

Furthermore, the Return on Investment (ROI) is calculated at 16.2%, signifying substantial cost savings and long-term profitability. The Internal Rate of Return (IRR), which measures the system's expected financial performance, is estimated at 19.1%, reinforcing the hybrid system's attractiveness for large-scale industrial applications. Additionally, the system achieves annualised savings of $4.56 million, further improving its financial viability over its operational lifetime.

Comparative studies support these findings. The International Atomic Energy Agency (IAEA, 2023b) has reported that nuclear-renewable hybrid energy systems, particularly those integrating Small Modular Reactors (SMRs), consistently demonstrate lower LCOE values than traditional fossil fuel-based power generation due to lower fuel costs and extended operational lifetimes. Similarly, IRENA (2021), Nyasapoh et al. (2022) and Nyasapoh et al. (2024) emphasised that renewable energy integration significantly reduces electricity costs across Africa, improving financial sustainability and long-term economic returns. From an economic standpoint, Nyasapoh et al. (2022) conducted a financial performance analysis of

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nuclear-renewable hybrid energy systems in Ghana using HOMER software. Their study revealed that while the cost of energy (COE) for residential consumers may still be high compared to conventional tariffs, the system is economically viable for bulk commercial consumers. They highlight that adopting nuclear-renewable hybrid systems can stimulate commercial activities, particularly for small and medium enterprises (SMEs), while supporting Ghana's long-term clean energy agenda. This financial feasibility aligns with the present study, demonstrating that a nuclear-renewable hybrid system can achieve an LCOE of $0.185/kWh, significantly lower than Ghana's 2024 grid tariff of $0.2804/kWh.

Moreover, this study highlights the potential cost savings compared to Ghana's projected 2025 power outlook, where total fuel expenditures for thermal power plants are estimated to exceed $1.25 billion (Ghana Energy Commission, 2024b). By adopting a nuclear-renewable hybrid system, Ghana can significantly reduce dependence on imported fossil fuels, lower electricity generation costs, and improve overall energy security and financial sustainability in the industrial sector.

Thus, the economic analysis underscores that the nuclear-renewable hybrid system presents a financially viable and cost-effective energy solution for industrial applications. It offers long-term economic benefits while ensuring reliable, clean, affordable electricity for sustainable industrialisation.

Environmental Benefits

The hybrid system presents substantial environmental benefits by achieving a CO_2 emissions reduction of 15,824,965 kg per year, aligning with Ghana's National Energy Transition Framework and global decarbonisation commitments under the Paris Agreement. The non-inclusion of fossil fuel-based generation significantly cuts greenhouse gas emissions, reducing reliance on diesel and natural gas.

Research supports the role of nuclear-renewable hybrid systems in climate change mitigation. Adelekan et al. (2024) integrating SMRs with renewables results in a drastic lowering of emissions compared to standalone nuclear or fossil fuel systems. The increasing need for decarbonisation and energy security drives the global transition towards cleaner and more sustainable energy alternatives.

According to Adelekan et al. (2024), energy transition policies worldwide are focused on shifting from fossil fuel-based systems to renewable energy, motivated by environmental concerns, economic competitiveness, and the need for energy security. The study further emphasises the role of regulatory frameworks, financial incentives, and technological advancements in shaping energy transition pathways. By integrating nuclear energy into renewable-based systems, countries can ensure a stable and low-carbon energy supply, mitigating the intermittency challenges of renewables such as wind and solar. This aligns with

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Ghana's energy transition goals, where the combination of SMRs and renewables provides a robust solution for industrial electrification. By achieving 30% renewable penetration, the hybrid system also supports Ghana's 2070 target of 20% installed renewable capacity (Ministry of Energy, 2023)**.** The deployment of nuclear power in Ghana's energy mix is projected to further reduce emissions by 7–8 million tons of CO_2 annually by 2030, of which SMRs integration with renewables could significantly impact.

Integrated energy system grid interaction

Integrating the hybrid energy system with Ghana's national grid provides significant operational and economic advantages by enhancing grid stability and facilitating energy trade. Table 1 presents the interaction of the hybrid energy system with the grid to ensure a stable power supply. The proposed system allows for annual energy exports of 206,079,408 kWh**,** while purchasing 25,039,502 kWh from the grid to balance supply-demand fluctuations. This results in a net energy surplus of 181,039,904 kWh, positioning the system as a major feed into the grid or possibly an electricity exporter within the West African Power Pool (WAPP).

Table 1: Grid Interaction of Nuclear Renewable Integrated Energy System

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge	Demand Charge	Total
January	0	22,575,992	-22,575,992	0	$0.00	$0.00	$0.00
February	0	24,479,124	-24,479,124	0	$0.00	$0.00	$0.00
March	24,617,760	2,863,116	21,754,644	100,709	$7.07M	$0.00	$7.07M
April	0	21,437,708	-21,437,708	0	$0.00	$0.00	$0.00
May	17,338	19,051,084	-19,033,746	10,496	$4,976	$0.00	$4,976
June	0	17,145,116	-17,145,116	0	$0.00	$0.00	$0.00
July	37,517	14,975,505	-14,937,988	10,515	$10,767	$0.00	$10,767
August	0	16,927,268	-16,927,268	0	$0.00	$0.00	$0.00
September	208,648	12,441,891	-12,233,243	25,089	$59,882	$0.00	$59,882
October	0	17,841,014	-17,841,014	0	$0.00	$0.00	$0.00
November	74,051	16,901,822	-16,827,770	19,163	$21,253	$0.00	$21,253
December	84,188	19,439,768	-19,355,580	25,176	$24,162	$0.00	$24,162
Annual	25,039,502	206,079,408	-181,039,904	100,709	$7.19M	$0.00	$7.19M

Monthly grid interaction patterns indicate that in certain months, no energy is purchased from the grid: January, February, April, June, August, and October**.** In contrast, in others, minimal purchases are made to compensate for variability in renewable generation. Notably, when the 100,709 kW peak load is recorded in March, 24,617,760 kWh is drawn from the grid, corresponding to an energy charge of $7.07 million. This is likely due to scheduled SMR refuelling, requiring temporary reliance on external power sources.

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Studies confirm that hybrid energy systems integrated with national grids improve reliability and create revenue streams through electricity sales. According to Zhang et al. (2024), grid-tied hybrid systems enhance energy security by providing surplus power during peak demand periods and reducing transmission losses. The study's ability to export 206,079,408 kWh annually aligns with Ghana's long-term energy strategy of expanding its electricity export market to neighbouring countries within the WAPP framework (Ghana Energy Commission, 2024b).

Furthermore, the grid-connected hybrid system presents new economic and environmental opportunities. In terms of revenue generation, the system generates $7.19 million annually from electricity sales, offsetting operational costs. Also, excess renewable electricity can be utilised for green hydrogen generation, supporting Ghana's clean energy transition. Finally, balancing the load variations and injecting surplus electricity enables the system to strengthen grid resilience, reducing the risk of blackouts.

The study's results and most current studies' discussions collectively reinforce the findings of the present research, demonstrating that integrating SMRs with renewable energy sources ensures a cost-effective and reliable electricity supply and supports national and global energy transition goals. Hence, incorporating nuclear-renewable hybrid systems in Ghana's industrial energy landscape presents an opportunity for enhanced energy security, economic growth, and environmental sustainability, making it a viable pathway for sustainable industrialisation in Africa.

Key policy recommendations for sustainable implementation of nuclear renewable hybrid energy systems

The successful implementation of nuclear-renewable hybrid energy systems to achieve the desired goals depends on several key factors. These factors include, but are not limited to:

National Energy Policy Reform and Investment Incentives: Accelerating the deployment of nuclear-renewable hybrid energy systems require the development of clear regulatory frameworks that support private sector participation and long-term investments in nuclear and renewable energy integration by policymakers. Establishing dedicated financial incentives, such as tax credits, feed-in tariffs for hybrid systems, and risk mitigation measures, can enhance investor confidence and encourage large-scale adoption.

Strengthening Infrastructure and Grid Modernization**:** A well-integrated hybrid system requires a modernised smart energy grid to ensure efficient energy distribution and stability. Investments in advanced grid management technologies, demand-response mechanisms, and digital infrastructure will optimise hybrid energy performance and enable surplus energy trading within Ghana and across the West African Power Pool (WAPP).

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Strategic Development of Local Capacity and Workforce: The successful implementation of hybrid energy systems necessitates technical expertise and skilled personnel in nuclear, solar, wind, and energy storage technologies. Policymakers should foster partnerships between government agencies, universities, and industry stakeholders to establish specialised training programs in hybrid energy technologies. This ensures that Ghana develops a strong workforce to support the transition.

Regional Energy Trade and Green Hydrogen Development: With the study's 206,079,408 kWh of annual surplus energy, Ghana can become a regional energy hub. By expanding energy trade agreements and investing in green hydrogen production, Ghana can diversify its energy economy, create new revenue streams, and enhance its global clean energy market competitiveness.

Strengthening Nuclear-Renewable Hybrid Research and Development (R&D): A dedicated R&D agenda is critical to optimising hybrid energy systems and addressing potential safety, reliability, and economic challenges. The government should support pilot projects and demonstration plants to refine hybrid system designs, test emerging energy storage technologies, and explore the feasibility of hydrogen-based storage as a long-term energy solution.

CONCLUSION

This study comprehensively assesses integrating Small Modular Reactors (SMRs) with renewable energy sources, mainly solar and wind, as a hybrid energy system for Ghana's sustainable and resilient industrial electrification. The results demonstrate that the proposed nuclear-renewable hybrid system requires 1,888,776 kWh daily and has a peak demand of 159,124 kW, ensuring a stable and efficient power supply for industrial applications. The economic feasibility analysis confirms that the system achieves a Levelized Cost of Energy (LCOE) of $0.1846/kWh, 34% lower than Ghana's 2024 grid tariff. Additionally, the system reduces CO_2 emissions by 15,824,965 kg annually, contributing to Ghana's National Energy Transition agenda and global decarbonisation efforts. These findings establish nuclear-renewable hybrid systems as a transformative energy solution capable of addressing the country's energy security challenges, reducing electricity costs, and enhancing industrial productivity.

Thus, integrating nuclear and renewable energy sources into a hybrid system represents a paradigm shift in Africa's energy landscape. The successful implementation of this strategy will enhance energy security, stimulate economic growth, and position Ghana as a leader in Africa's clean energy transition. This research is a critical reference for policymakers, energy planners, and industry stakeholders, offering a practical roadmap for accelerating the adoption of hybrid energy solutions and ensuring a sustainable and prosperous energy future for Ghana and beyond.

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Despite this study's promising results, further research is required to analyse long-term system performance, assess the impacts of policy interventions, and explore scalable business models for hybrid energy adoption in other African economies.

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