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HYBRID NUCLEAR AND RENEWABLE SYSTEMS FOR GHANA'S ENERGY TRANSITION AND SUSTAINABLE DEVELOPMENT

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Abstract

Ghana's electricity sector remains heavily dependent on fossil fuels, leading to high generation costs and growing environmental pressures. This study examined a three-case discount rate of 8%, 10%, and 12% for a nuclear–renewable hybrid energy system (N-R HES) that integrates a Small Modular Reactor (SMR) with solar and wind resources. The analysis, conducted using the Hybrid Optimisation of Multiple Energy Resources (HOMER) software, focuses on improving energy security, economic viability, and sustainability. The proposed hybrid energy system, comprising SMR, solar PV, wind generation, and battery storage, demonstrates strong technical resilience, significantly reducing reliance on grid electricity, particularly during SMR refuelling periods. Under the 10% base-case scenario, the system achieves a Levelised Cost of Energy (LCOE) of USD 0.1846/kWh, well below Ghana's industrial grid tariff of USD 0.2804/kWh. Financial performance remains robust, with an Internal Rate of Return of 19.1%, annual savings of USD 4.56 million, a payback period of 5.12 years, and a Net Present Value of USD 32.6 million. Comparative results across the 8%, 10%, and 12% discount rates show consistent technical output but expected financial variations due to capital-cost sensitivity. The lower discount rate (8%) delivers the strongest investment performance, while the 12% case remains viable despite reduced long-term returns. Overall, the N-R HES model offers a cost-effective, low-carbon, and reliable pathway for Ghana's industrial and national energy transition objectives..

Keywords
hybrid energy system, synergy, sustainable energy, levelised cost of energy (LCOE), HOMER Pro simulator, small modular reactor (SMR), renewable energy, industrial development, economic growth

Introduction

The growing imperative to mitigate greenhouse gas (GHG) emissions, prompted by the adverse impacts of climate change, holds significant importance (IPCC, 2021; US EPA, 2023). According to IRENA (2023), Least Developed Countries (LDCs) with less than 5% of global GHG emissions are vulnerable to severe climate impacts. The production of electricity from renewable energy sources, such as solar, wind, and hydropower, holds the promise of being sustainable and clean (Nyasapoh, 2018). Because of this, the LDC wants to increase investment in renewables significantly, reaching over 105 GW by 2030 despite the lack of funds. Moving from the 2022 current installed capacity, nearly the system will require USD 107 billion to have an unconditional installation of 28 GW through domestic and international investments, in addition to the conditional 30 GW conditional investment support (IRENA, 2023).

Based on this, achieving the Paris Agreement's target of keeping the rise in global temperature to less than 2°C will require the use of all low-carbon technologies, including nuclear and renewable energy sources (IAEA, 2023b). There are numerous initiatives underway to decrease the amount of fossil fuels used in the production of electricity as the world moves toward a net-zero economy (IEA, 2023; Nyasapoh et al., 2023a). But for the most part, the nation's energy demands have been met largely by fossil fuels like natural gas and oil since 2015 (Nyasapoh et al., 2022d). At present, the country's electricity generation mix is comprised of 69% fossil fuels, 29% hydropower and 2% other renewables, mainly solar and mini hydropower (Commission, 2023). Ghana's excessive reliance on fossil fuels increases carbon emissions, which exacerbates the climate catastrophe, and exposes the country to the volatility of the world energy markets (MESTI, 2019, 2021).

Energy transitions do not, however, eliminate the conventional threats to energy security. Meaningful progress may be hampered in the absence of strict policies to promote and close energy investment gaps, particularly for emerging countries (IEA, 2023). The International Atomic Energy Agency (IAEA) released a historic declaration at the recently concluded COP28. The declaration was supported by countries all over the world, asserting that combating climate change necessitates using clean energy sources like nuclear power (IAEA, 2023a).

To meet Ghana's energy needs while lowering the country's carbon footprint, it is critical to investigate novel alternatives as the nation works to uphold its international obligations

(Environmental Protection Authority, Ghana, 2020; MESTI, 2021). The adoption of a hybrid energy system that combines nuclear and renewable energy sources is emphasised in this study as a critical approach for Ghana's energy transformation agenda (Nyasapoh et al., 2022d). Ghana can expedite its transition to a low-carbon, sustainable future by leveraging the distinct advantages of both nuclear and renewable technologies (Ministry of Energy, 2023a; Nyasapoh et al., 2023a). The above situation makes it imperative for Ghana to switch to greener, but more sustainable energy sources to meet its energy needs and uphold its international obligations.

An established technique that has been utilised for a long time to provide electricity with low carbon emissions is nuclear energy (IAEA, 2023c). Nuclear energy has various benefits which Ghana can derive from for sustainable national development, ranging from improved energy security, clean and baseload, to addressing the intermittent nature of renewable energy sources (Debrah et al., 2020). Ghana has an abundance of renewable energy resources that can be used to meet the nation's energy demands while cutting carbon emissions (Nyasapoh et al., 2022a). These resources include wind and sunlight (Ministry of Energy, 2019). On the other hand, these sources provide unique difficulties, including seasonality and erratic behaviour (Arefin et al., 2021). While minimising the impact of the difficulties that come with intermittent renewable energy sources, Ghana must take advantage of the enormous potential and link with other clean energy sources such as nuclear energy (Esteves and Gabar, 2023; Pérez-Arriaga, 2012). Such an act will ensure a path for a sustainable electricity generation mix (Nyasapoh et al., 2023b) that will also drastically lower Ghana's carbon footprint (Ministry of Energy, 2023a). Traditionally, hybrid energy systems integrate renewable energy sources with generators powered by fossil fuels (Acakpovi et al., 2017). However, because of their significant carbon emissions, these arrangements frequently pose environmental issues (Gabar and Abdussami, 2019). However, a more dependable and sustainable option is provided by combining nuclear Small Modular Reactors (SMRs) with renewable energy sources, primarily solar and wind (Suman, 2018).

Ghana's energy transition will be substantially aided by a hybrid energy system that blends nuclear and renewable energy sources, such as nuclear and wind (Nyasapoh et al., 2022d). The intermittent characteristic of renewable energy sources, such as wind and solar, can be mitigated by nuclear power, which can offer a steady and uninterrupted supply of electricity (IAEA, 2023e). More importantly, the Intergovernmental Panel on Climate Change (IPCC) mitigation pathways also highlight the need for a combination of nuclear power and other low-carbon energy sources (IAEA, 2023d).

This study examined a three-case discount rate of 8%, 10%, and 12% for a nuclear–renewable hybrid energy system (N-R HES) that integrates a small modular reactor (SMR) with solar and wind resources. The analysis, conducted using the Hybrid Optimisation of Multiple Energy Resources (HOMER) software, focuses on improving energy security, economic viability, and sustainability. Critical areas of discussion also focused on harnessing nuclear and renewable hybrid energy systems (N-R HES) synergy and the advantages of the needed energy transition. The study aims to offer insights that can direct Ghana's energy transition plan and assist the nation in achieving its climate goals through a thorough analysis of such a system.

The Role and Potential of Nuclear Energy in Ghana's Energy Transition

The role of nuclear energy emerges as a crucial and transformative force in Ghana's ambitious pursuit of an energy transition that meets its expanding energy demands while being in line with international climate targets (Ministry of Energy, 2023b). Ghana and five other sub-Saharan African countries, including Uganda, Nigeria, Rwanda, Kenya, and Zambia have committed to incorporating nuclear energy into their energy mix between 2030 and 2037 (Nuclear Business Platform, 2023). Thus, nuclear energy is a strong contender in the transition to a greener and more secure energy future because of its distinct position as a reliable, low-carbon baseload power source. This complex conversation under this section takes place against the backdrop of worries about climate change and the pressing need for clean, dependable baseload power for Ghana.

Ghana's nuclear power agenda began in 1963, and it is currently moving forward at a rapid rate (Debrah et al., 2020; Nuclear Engineering International, 2023). The potential for nuclear power in Ghana extends beyond theoretical discussions, encompassing technical feasibility, economic viability, and regulatory readiness (Debrah et al., 2020; IAEA, 2017, 2021). To assess the suitability of Ghana's nuclear power, an exploration of resource availability, infrastructure preparedness, financial considerations, and regulatory frameworks is essential (IAEA, 2017).

Potential of Renewable Energy in Ghana's Energy Transition

As Ghana embarks on its transformative journey toward a sustainable and low-carbon energy future, the integration of renewable energy sources emerges as a cornerstone of this profound transition (Ministry of Energy, 2023a). Renewable energy, with its environmentally sustainable and technologically advanced solutions, is poised to play a pivotal role in reducing greenhouse gas emissions while satisfying the burgeoning energy needs of the nation (Ministry of Energy, 2019; Parliament of Ghana, 2020).

Solar Energy

The abundant and consistent sunlight gracing the Ghanaian landscape presents an extraordinary opportunity to harness the power of solar energy (Commission, 2019). In addition, the continuous advancement of photovoltaic technology has elevated solar power to the forefront of the renewable energy revolution (Nassar et al., 2025; Panagoda et al., 2023; Ra-

machandran et al., 2022). Ghana is ideally situated to receive solar radiation, which makes it ideal for uses combining thermal and electrical energy (Commission, 2019).
The average daily solar radiation over the country's regions ranges from 4.4 to 5.6 kWh/m2/day, with a very low diffused radiation of about 32%. The average daily sunshine duration in Ghana's middle belt varies from 5.3 hours in cloudy, semi-deciduous forest zones like Kumasi to 7.7 hours in arid, savannah zones like Wa in the north of the country (Commission, 2019). Ghana currently generates 162 GWh of renewable energy in total (Commission, 2023).

Wind Energy

Ghana's extensive coastal region, caressed by steady ocean winds, provides a strategic advantage for harnessing wind energy (Ministry of Energy, 2019). Wind turbines positioned along the coast have the potential to capture and convert kinetic energy into a consistent supply of clean electricity (Commission, 2019). Although Ghana has not yet seen a large installation of wind energy, it is estimated that the nation has approximately 300 MW of wind farm capacity as potential for future expansion (Ministry of Energy, 2019). With average annual wind speeds of 4 to 6 m/s at 50 m above sea level along the coast and islands, the nation's wind potential is categorised as marginal. NREL satellite data indicates that wind speeds in the country's mountainous regions, particularly in Ghana and Togo, exceed 8 metres per second (Commission, 2019).

Overcoming Renewable Challenges for Clean Hybrid Energy Systems

Overcoming Challenges in Renewable Energy Deployment

While the potential for renewable energy in Ghana is vast, it is vital to acknowledge the challenges that must be addressed on the path to widespread adoption (Cosgrove et al., 2023; Pérez-Arriaga, 2012). The challenges associated with renewable energy sources such as wind and solar range from addressing intermittency issues to ensuring smooth integration with the existing energy grid (Kabeyi and Olanrewaju, 2022). The evolving policy and regulatory frameworks in Ghana, mainly the Renewable Energy Amended Act (Ministry of Energy, 2020), the Renewable Energy Master Plan (Ministry of Energy, 2019), and the 2021 National Energy Policy (Ministry of Energy, 2023b) provide a comprehensive understanding of the supportive measures in place and areas that require further development.
Further, to maintain supply sustainability, Ghana's energy mix needs to pay close attention to the intermittent nature of renewable energy sources like wind and solar power. Nuclear power, which is both a baseload and a clean energy source, is one alternative baseload electricity generation alternative that can increase the number of benefits (Jenkins et al., 2018). Nuclear energy systems are flexible owing to three main mechanisms that include the core ramping, integrated energy systems with various byproducts and thermal storage (Bragg-Sitton et al., 2020). Hence, hybrid energy systems that combine nuclear and renewable energy sources take into account the advantages of both to supply the grid with dependable, sustainable and low-carbon electricity generation (IAEA, 2023e). Thus, imperative to further explore how Ghana's energy system may best utilise the complementary effects of nuclear power and intermittent renewable energy sources, particularly wind and solar.

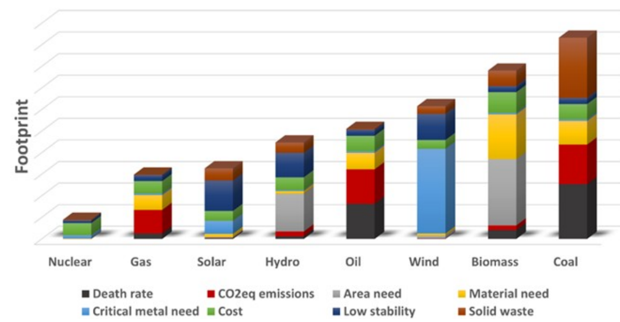

Figure 1. Total footprint by source of energy (esthammer, 2020)

Harnessing the Synergy of Nuclear and Renewable Hybrid Energy Systems

Hybrid energy systems, combining nuclear and renewable energy sources, are gaining significant attention in recent times as a promising solution for sustainable energy transition (Nyasapoh et al., 2024). To varying degrees, all energy sources have an impact on the economy, ecology, climate, and health. These are significant elements that need to be taken into account when evaluating the future energy mix (esthammer, 2020). Despite the drawbacks of both nuclear power and sporadic energy sources like wind and solar power, a nuclear-renewable hybrid energy system can be created by integrating the two carbon-free technologies (Arefin et al., 2021). Figure 1 shows the carbon footprint of various energy sources. Hence, the best way to address the obvious problems with renewable energy is to combine it with an energy source, such as nuclear power (esthammer, 2020).
As a result of their zero-emission characteristics, nuclear and renewable energy sources have evolved to prominence (IAEA, 2023e). The synergy is highly important because of the growing significance of flexibility as a result of the extensive use of intermittent, low-carbon energy sources like solar and wind. As a result, it has become increasingly important to quantitatively test the hybrid nuclear and renewable energy systems for Ghana's energy transition.

Materials and Methods

The methodology of the study provides a structured approach to analysing the integration of nuclear (i.e. a small modular reactor (SMR)) with renewable energy sources (i.e. solar and wind) for sustainable power generation. The study adopted Hybrid Optimisation of Multiple Energy Resources (HOMER) Pro software for the modelling. With a suggested energy system that improves energy security and reliability issues, the HOMER Pro software is extensively used for hybrid energy system optimisation. This makes the software a feasible model

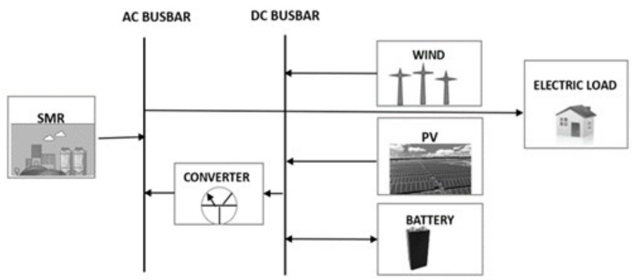

Figure 2. Conceptual Framework of N-R HES (Source: Author's draft)

for integrating renewable and clean energy systems studies in developing nations like Ghana.

Conceptual Framework of the Hybrid Energy System

Hybrid energy systems traditionally combine fossil fuel-based generators with renewable energy sources (Acakpovi et al., 2017). However, such configurations often present environmental challenges due to high carbon emissions (Gabar and Abdussami, 2019). In contrast, integrating nuclear Small Modular Reactors (SMRs) with renewable energy sources, mainly solar and wind, offers a more sustainable and reliable alternative (Suman, 2018). As illustrated in the conceptual framework in Figure 2, solar and wind energy are inherently intermittent and typically generate direct current (DC), whereas SMRs provide a stable and continuous alternating current (AC) supply (IAEA, 2023e). To ensure seamless integration, a converter is used to transform stored DC power into AC when necessary, aligning with the system's alternating current demand. Additionally, the hybrid system allows excess energy generated from renewables to be stored for later use, optimising overall efficiency.

This hybrid configuration is designed as a complementary energy system, leveraging the strengths of each source to enhance energy security and sustainability. Thus, the combination of nuclear small modular reactor (SMR) and renewable energy minimises reliance on battery storage while ensuring continuous power generation (Jevremovic and Heek, 2018). Nuclear power reactors, particularly Generation III and III+ SMRs, are designed for flexible operations, allowing them to function as backup sources for intermittent renewable energy, such as solar and wind (Bragg-Sitton et al., 2020). The adaptability of SMRs in load-following mode further enhances system resilience and reliability (Arefin et al., 2021).

System Sizing of the Nuclear-Renewable Hybrid Energy system

The hybridisation incorporates advanced cognitive control mechanisms to optimise energy dispatch, thereby improving efficiency and minimising reliance on battery storage (IAEA, 2023e). As per the system sizing of the hybrid energy system in the software, the total power available at any given time t is formulated as in Equation 1.

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

Where:

- $P_{total}(t)$: Net power available at time t.
- $P_{SMR}(t)$: Power generated by the Small Modular Reactor (SMR), often modeled as a constant or slightly variable output based on operational constraints.
- $P_{solar}(t)$: Solar PV power output, computed as Equation 2.

$$P_{solar}(t) = A_{PV} \times \eta_{PV} \times G(t) \quad (2)$$

  Where A_{PV} is the panel area, η_{PV} is the efficiency, and $G(t)$ is the solar irradiance at time t.

- $P_{wind}(t)$: Wind turbine power generation, estimated using the wind power equation in Equation 3.

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

  Where C_P is the power coefficient, ρ is air density, A is the swept area, and $v(t)$ is the wind speed at time t.

- $P_{battery}(t)$: Net power from the battery system, which accounts for charging and discharging, given by Equation 4:

$$P_{battery}(t) = \eta_{ch} P_{charge}(t) - \frac{P_{discharge(t)}}{\eta_{dis}} \quad (4)$$

  Where η_{ch} and η_{dis} are the charging and discharging efficiencies, respectively.

- $P_{load}(t)$: Electricity demand at time t, which can vary dynamically based on the community's consumption pattern.
- $P_{loss}(t)$: System losses due to transmission, conversion, and other inefficiencies.
- $P_{grid}(t)$: Power exchange with the grid (if applicable), positive when importing power and negative when exporting excess energy.

The capacity factors of all energy sources were assessed and calculated based on the generation capacity ratings provided by the (US Department of Energy, 2025). This analysis played a key role in determining the appropriate technology sizes for the modelling.

The hybrid system is designed for a daily load of about 1.89 GWh and a peak demand of 159 MW. It integrates a 60 MW Small Modular Reactor (SMR) as a firm baseload source, covering 70% of the daily energy demand. The remaining 30% electricity demand is supplied by renewables with 163.4 MW of installed photovoltaic (PV) capacity and 2.0 MW of installed wind capacity. A 157.2 MWh battery storage system is included to smooth variability and enhance grid stability. This configuration ensures a balanced and sustainable electricity supply by leveraging nuclear power for reliability while maximising renewable energy contributions (Esteves and Gabar, 2023; Nyasapoh et al., 2022d; Ruth et al., 2017).

Discount Rate Variation and Economic Parameters

The study uses a 10% discount rate, which is consistent with the energy supply analysis used in Ghana's Integrated Power System Master Plan (IPSMP), of the Energy Commission of Ghana (Commission, 2023). In order to identify the optimal investment options for the energy system and to give policymakers unambiguous recommendations, the discount rate variations of 8% and 12% in comparison to the 10% base scenario are assessed. The Public Utilities Regulatory Commission's (PURC, 2024) grid supply price of 0.2804 USD/kWh (28.04 cents) is compared to the cost of energy obtained from the study for the financial evaluation (PURC, 2024). The Energy Commission of Ghana is the source of the electricity demand statistics, which focuses on a mining site in order to evaluate its practicality. The economic matrices considered in the study are discussed below:

Levelised Cost of Energy (LCOE)

The LCOE as used in this study represents the average cost per unit of electricity generated over the lifetime of an energy system, accounting for capital, operational, maintenance, and fuel costs. It is crucial in the economic analysis of every major power project as it allows for the comparison of different energy technologies on a cost-per-kilowatt-hour ($/kWh) basis. In a nuclear-renewable hybrid energy system investment, a lower LCOE indicates a more cost-effective and competitive energy solution compared to any other energy-based system. The LCOE representation in the model for the study analysis is as seen in Equation 5.

$$LCOE = \frac{\sum(C_{capital} + C_{operation} + C_{maintenance} + C_{fuel})}{\sum E_{generated}} \quad (5)$$

Where:

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

Net Present Value (NPV)

NPV is the difference between the present value of all costs and revenues over a system's lifetime. A positive NPV indicates that an investment is financially viable, while a negative NPV suggests a loss. In the economic analysis of a hybrid energy system, NPV helps determine whether the long-term benefits outweigh the upfront capital expenditure, ensuring financial sustainability. The NPV representation is seen as Equation 6.

$$NPC = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t} \quad (6)$$

Where:

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

Internal Rate of Return (IRR)

IRR is the discount rate at which the net present value (NPV) of an investment becomes zero, meaning the project breaks even in terms of profitability. A higher IRR suggests that the hybrid system yields strong financial returns, making it attractive for investors. In the case of integrating nuclear and renewable energy, IRR helps evaluate the financial feasibility of the system by measuring its profitability over time.

Return on Investment (ROI) and Payback Period

The payback period (PP) helps determine how long it will take the project to recoup its initial expenditure, while the ROI evaluates the system's profitability. The ROI and Payback Period computations are shown in Equation 7 and Equation 8.

- ROI:

$$ROI = \frac{\text{Net Profit}}{\text{Total Investment}} \times 100 \quad (7)$$

- PP:

$$PP = \frac{C_{capital}}{\text{Annual Savings}} \quad (8)$$

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

Annualised Cost Savings

Annualised cost savings refer to the reduction in yearly operating costs achieved through system optimisation. It is calculated by spreading the total savings over the project's lifetime, making it easier to assess long-term financial benefits. In a nuclear-renewable hybrid energy system, annualised cost savings demonstrate how much money is conserved by reducing reliance on fossil fuels, lowering operational costs, and improving system efficiency.

Each of these metrics plays a critical role in evaluating the competitiveness and financial viability of nuclear-renewable hybrid energy systems. They provide essential insights into cost efficiency, investment returns, and long-term savings, aiding in informed decision-making for energy sector stakeholders.

Source of Data

HOMER Pro Software was used to acquire the data on solar, wind, and battery storage as well as the important comparisons from national and international energy authorities to fit the study's characteristics and location.

Solar and Wind Resource Data

The National Aeronautics and Space Administration (NASA's) Surface Meteorology and Solar Energy Database and other publicly accessible meteorological datasets, including the National Renewable Energy Laboratory (NREL) and Global Solar Atlas, provided the solar resource data used in HOMER Pro for this study (World Bank Group, 2024a). To guarantee an accurate depiction of solar irradiance levels in the study area, the data were loaded into HOMER Pro (HOMER Energy, 2023).

The study's wind resource data came from NASA, the Global Wind Atlas (GWA), and local weather stations (World Bank Group, 2024b). To simulate wind energy potential, HOMER Pro needs wind speed information at a particular height (HOMER Energy, 2023). For both solar and wind energy sources, according to the (Commission, 2019), Ghana's Energy Profile of Districts was also contracted out.

Battery Storage, Electricity Demand and SMR Data

To store extra energy from solar and wind power sources, a lithium-ion battery storage system was modelled in HOMER Pro. By supplying backup power at times when renewable energy output is low, the storage system guarantees grid stability and dependability (HOMER Energy, 2023). The electricity demand data for the mining community was sourced; however, the specifics of the data cannot be revealed because of confidentiality issues. The International Atomic Energy Agency (IAEA) data repository provided the majority of the information on Small Modular Reactors (SMRs) used in this study (IAEA, 2025a,b).

Results and Discussion

The proposed energy system for the study combines a Small Modular Reactor (SMR) with solar and wind resources to deliver a more stable and cost-effective electricity generation. To understand how the system performs under different financial conditions, three discount rates, 8%, 10%, and 12% scenarios, were evaluated. The 10% rate is treated as the base case, while the 8% and 12% scenarios help illustrate how changes in the cost of capital influence the behaviour of the nuclear–renewable hybrid system (N-RHES). The discussion begins by outlining the existing energy setup and the characteristics of the proposed hybrid energy system in the base case. The subsequent sections then compare the results across the three discount-rate scenarios, highlighting how each rate affects system costs, performance, and overall economic viability.

Current energy system

The target community presently relies on a hybrid electricity supply made up of a 163 MW photovoltaic (PV) array, a 60 MW Small Modular Reactor (SMR), grid power, and a converter. During daylight hours, solar power provides the bulk of the electricity, while the SMR ensures continuity at night and during cloudy or high-demand periods. Although

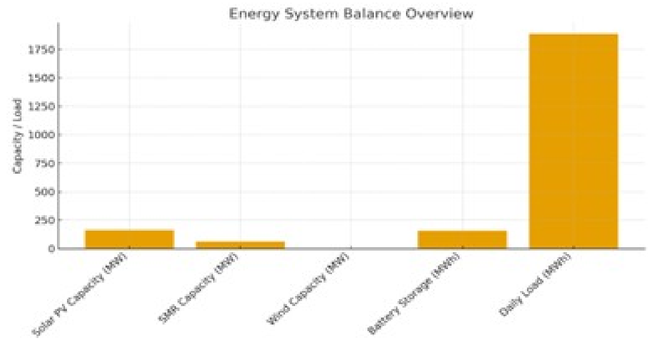

Figure 3. Energy System Balance Overview (Source: Author's draft)

this arrangement meets the community's daily demand, which averages 1.89 GWh/day with a peak requirement of 159 MW, it is financially demanding. Thus, the absence of any energy storage system means that excess daytime solar output cannot be retained for evening use.

The illustration in Figure 3 illustrates both the current and proposed energy systems. The illustration shows that the current system's installed generation capacities are substantial, yet the lack of storage causes a persistent mismatch between available daytime energy and actual load requirements, reinforcing dependence on grid electricity.

Consequently, the system frequently turns to expensive, fossil-fuel-based grid electricity due to Ghana's heavy dependency on fossil fuels (Nyasapoh et al., 2022a, 2023a, 2022d), with 61% in the generation mix (Commission, 2025). The situation of the current energy system occurs particularly when the SMR is offline for scheduled maintenance or refuelling. As a result, the study revealed that the reliance on the grid drives annual operating costs to USD 66.3 million, creating both economic strain and operational exposure.

Proposed Hybrid System

To overcome the limitations of the existing setup, a more integrated hybrid energy system is proposed. The new configuration retains the SMR and solar PV but adds wind generation (2 MW) and battery storage (157 MWh) as represented in Figure 3. Together, these components create a more flexible and resilient architecture capable of balancing supply and demand throughout the day, as stated in the study by Esteves and Gabar (2023) and Nyasapoh et al. (2025). The shift from the current configuration to the proposed hybrid leads to a measurable reduction in annual operating expenditure, as depicted in Figure 4, demonstrating the economic efficiency gained through storage integration and diversified renewable inputs.

In the enhanced energy system arrangement, the SMR maintains its role as the stable baseload provider. Solar PV continues to deliver the main daytime supply, while wind power contributes during periods when solar intensity drops, particularly in the late evenings and early mornings. The battery unit bridges the gap, capturing excess solar and wind output for release when needed. This coordinated interplay significantly reduces dependence on the grid and improves overall system

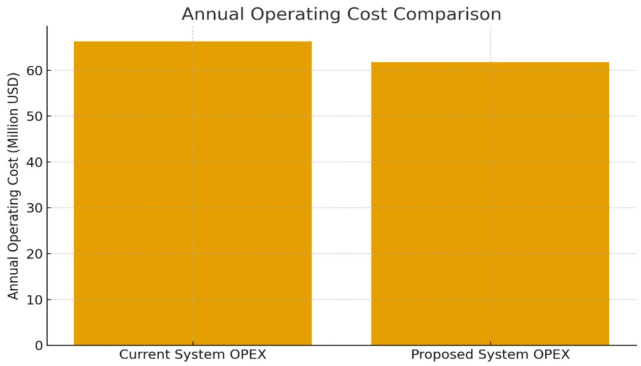

Figure 4. Annual Operating Cost Comparison (Source: Author's draft)

Table 1. Project Performance Summary

Parameter	Value
Simple Payback	5.12 years
Return on Investment (ROI)	16.2%
Internal Rate of Return (IRR)	19.1%
Levelised Cost of Energy (LCOE)	USD 0.1846/kWh
Total Net Present Cost (NPC)	USD 1.604 billion
Net Present Value (NPV)	USD 32.6 million
Capital Investment	USD 24.8 million
Annualised Savings	USD 4.56 million
Operating Cost	USD 61.8 million/year
Nominal Discount Rate	10%

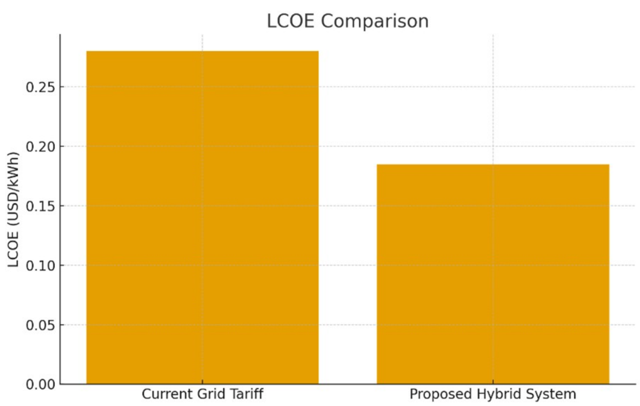

Figure 5. LCOE Comparison Chart (Source: Author's draft)

reliability (Zhang et al., 2024).
The financial performance summary in Table 1 provides detailed numerical evidence supporting the improvement in the proposed hybrid energy system.
Furthermore, the reduction in the cost of electricity generated by the proposed hybrid system is central to the study's findings, which is also supported by the studies of Gabar et al. (2020) and Nyasapoh et al. (2022b). Figure 5 highlights the notable decline in the Levelised Cost of Energy, confirming that the proposed system delivers electricity at a significantly lower cost than both the existing arrangement and the prevailing national grid tariff.

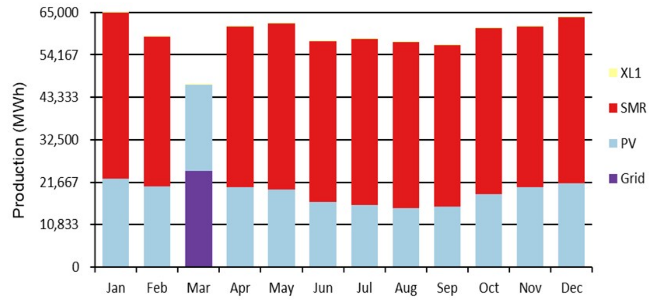

Figure 6. LCOE Comparison Chart (Source: Author's draft)

Economic Interpretation

The financial outcomes clearly illustrate the benefits of the study's proposed hybrid energy system model. Thus, annual operating expenses fall from USD 66.3 million in the current system to USD 61.8 million, yielding USD 4.56 million in yearly savings. With a payback period of just over five years and an IRR of 19.1%, indicating that the project shows strong investment appeal. Perhaps the most compelling improvement is the reduction in the Levelised Cost of Energy (LCOE) to USD 0.1846 per kWh, which is significantly lower than Ghana's 2024 PURC grid tariff of USD 0.2804 per kWh for industries (PURC, 2024). This difference confirms that the hybrid nuclear–renewable system not only provides cleaner energy but also generates electricity at a lower cost than the national grid for industrial enclaves.
Thus, the proposed system enhances operational flexibility, strengthens energy security, and reduces long-term expenditure. This positions the proposed energy system as a highly sustainable and economically competitive solution for the mining and other industrial or major power off-takers.

Technical Resilience and Monthly Electricity Generation Profile of the Hybrid System

Figure 6 presents the monthly electricity generation mix for the nuclear–renewable hybrid energy system (N-R HES) across the three discount rate (8%, 10% and 12%) scenarios. Despite differences in financial assumptions, the overall pattern of electricity supply remains largely consistent. In each scenario, the Small Modular Reactor (SMR) forms the dominant and most stable portion of the energy mix, appearing as a strong continuous band throughout the year. This firm's output is briefly interrupted only during the scheduled refuelling period in March for the study, creating a visible dip in the monthly profile of the energy system.
Complementing the SMR is the solar PV contribution, which varies naturally with Ghana's climate (Commission, 2019). The figure shows higher solar generation during the dry season, when sunlight is abundant, and slightly reduced production during the rainy months. Wind power plays a modest role, offering supplementary renewable output when conditions allow. Grid imports appear only during the SMR refuelling month, most notably in March. This situation shows that reliance on external supply is minimal once the hybrid config-

uration is established.
Although the overall energy mix remains broadly similar, the system shows slight differences in behaviour under the different discount rates of 8%, 10%, and 12%.

10% Discount Rate (Base Case)
The 10% discount rate scenario forms the reference for comparing the 8% and 12% discount rate cases. In the base case, the hybrid energy system balances nuclear, solar, wind, and storage in a way that keeps monthly supply consistent and minimises grid purchases. The SMR remains the anchor of the energy mix, while the battery captures mid-day solar excess to support evening demand.

8% Discount Rate Scenario
When the discount rate is reduced to 8%, the system becomes marginally more favourable for capital-intensive assets. As a result, both solar PV and battery storage are used efficiently across the year, and operational costs remain slightly higher than in the 12% case but lower than the existing system. The general shape of the generation profile remains the same, indicating strong SMR support, stable solar variation, and very limited grid imports.

12% Discount Rate Scenario
At a higher discount rate of 12%, the model adjusts the configuration to reduce upfront investment pressure. The solar PV installed capacity remains close to 161 MW, but the wind capacity drops to a token level, while the battery size stabilises around 159 MWh. Even with these adjustments, the system still produces nearly the same annual energy as the lower discount-rate scenarios. However, the higher discount rate increases the system peak to about 180 MW, compared to 165 MW in the 8% case, requiring a larger converter. The hybrid structure at 12% nevertheless lowers the annual operating cost to USD 61.3 million, slightly below the 8% scenario. This improvement results from more effective use of the battery, which reduces the March grid purchases and increases direct utilisation of mid-day solar through the upsized converter. Despite these operational gains, the LCOE rises under the 12% discount rate because the cost of financing becomes the dominant driver.
The electricity generation mix across the three discount rate scenarios reinforces the technical robustness of the proposed N-R HES. The SMR provides the backbone of supply, solar PV contributes a substantial share, particularly in the dry months, and battery storage enhances flexibility by smoothing daily fluctuations and reducing dependency on grid electricity. Even under more financially constrained conditions, the hybrid system maintains a reliable and stable monthly output profile, demonstrating its suitability for Ghana's long-term energy transition strategy.

Comparative Assessment of Cost-Effectiveness and Long-Term Energy Sustainability
Figure 7 illustrates the cumulative cash-flow trajectory of the hybrid nuclear–renewable energy system under the 10% discount-rate scenario, that serves as the base case. The curve rises sharply in the early years, reflecting the strong initial savings produced by the system, and then gradually levels off as it approaches year 30. This characteristic saturation pattern is typical of capital-intensive infrastructure, where the bulk of financial returns accrue early, followed by a long period of stable but slower growth.

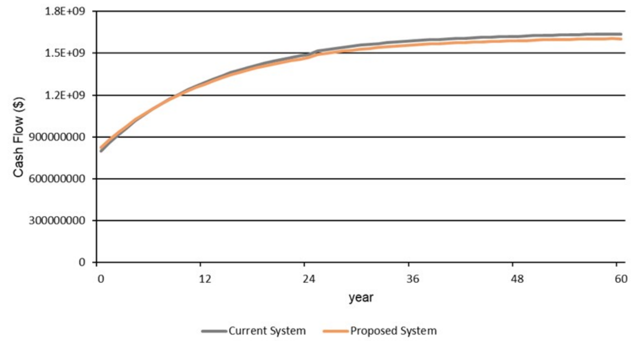

Figure 7. Cumulative Cash Flow over Project Lifetime (Source: Author's draft)

Comparatively, the curve for the 12% discount rate scenario consistently remains below the 8% and 10% discount rate scenario curves. This is expected per studies of Mignacca and Locatelli (2020), Islam (2018) and Nyasapoh et al. (2022c). Thus, when future revenues from long-lived assets such as SMRs and solar PV are discounted more heavily, their present value diminishes, resulting in a lower cumulative cash-flow outlook even when the physical performance of the system remains unchanged.

Comparative Cost Metrics Across Discount Rates
Across all scenarios, the hybrid configuration proves financially viable, but the degree of cost-effectiveness shifts with the discount rate:

12% Discount Rate
At the highest discount rate of 12%, the Levelised Cost of Energy (LCOE) settles at USD 0.205/kWh, with a Net Present Value (NPV) of USD 24.2 million and an Internal Rate of Return (IRR) of 20.8%. The payback period is 4.72 years, supported by a capital investment of USD 22.8 million. While still profitable, the higher financing cost compresses long-term returns.

10% Discount Rate (Base Case)
Under the base case, the project demonstrates stronger financial performance with an LCOE of USD 0.185/kWh. The NPV stands at USD 32.6 million, and an IRR of 19.1%, with payback achieved in 5.12 years for a USD 24.8 million capital cost. The cash-flow curve climbs more rapidly and reaches a higher plateau than the 12% scenario, reflecting healthier long-term value.

8% Discount Rate

With a lower cost of capital, the system achieves its best financial performance. The LCOE falls to USD 0.162/kWh, while the NPV rises markedly to USD 49.1 million, and the IRR improves to 23.0%, with the shortest payback period of 4.3 years on a USD 18.7 million investment. The cash-flow curve shows the fastest rise and the highest cumulative returns due to the relatively favourable treatment of long-term generation benefits.

As a result, the differences in curve shape, slower initial acceleration and a lower ultimate plateau at 12%, stem purely from the mathematics of discounting. Nuclear and solar assets deliver value steadily over decades, but the financial weight of those future savings shrinks as the discount rate increases. The physical performance of the system does not change, rather, the perceived value of future benefits is reduced when financial conditions are less favourable.

Despite the financial variations, all three cases, 8%, 10% and 12% confirm the long-term sustainability of the nuclear-renewable hybrid energy system (N-R HES). The integration of firm nuclear baseload with variable renewables, mainly solar and wind and battery storage ensures consistent energy availability with minimal grid dependence. The declining LCOE across lower discount rates demonstrates that the system becomes even more competitive when financing conditions improve. This situation strengthens the case as a sustainable long-term solution for Ghana's energy transition.

Conclusion

This study assessed a nuclear–renewable hybrid energy system (N-R HES) integrating a Small Modular Reactor (SMR) with solar, wind, and battery storage. Using HOMER software, the system was evaluated under three discount rates, 8%, 10%, and 12%, to determine the study's N-R HES technical performance, cost-effectiveness, and long-term sustainability. The study's results show that the hybrid system provides a stable and balanced supply, with the SMR serving as the baseload and renewables supported by storage to minimise grid dependence. Under the 10% base case, the system achieves an LCOE of USD 0.1846/kWh, lower than the national industrial tariff, while delivering strong financial outcomes, including annual savings of USD 4.56 million, a payback period of 5.12 years, an IRR of 19.1%, and an NPV of USD 32.6 million.

Across all discount rates, the technical performance remains consistent, confirming the system's robustness. Financial variation across the 8%, 10%, and 12% scenarios reflects sensitivity to capital cost assumptions, with the 8% case offering the highest financial returns. Overall, the N-R HES enhances energy security, reduces operational costs, strengthens system resilience during SMR refuelling, and supports Ghana's sustainable energy development anchored on the transition goals. While the study's system is viable, key challenges not assessed by the study include but not limited to, high upfront capital costs, nuclear regulatory requirements, grid integration needs, and public acceptance issues. Addressing these barriers will be essential for smooth deployment and sustained energy benefits.

Recommendations

To advance Ghana's clean energy transition and maximise the benefits of the proposed nuclear-renewable hybrid energy system (N-R HES), the study recommends the following:

Strengthen Policy and Regulatory Frameworks: policymakers should consider developing clear nuclear and hybrid-energy policies, streamlined licensing processes, and incentives that attract private investment while ensuring adherence to international nuclear safety standards.

Adopt Innovative Financing Approaches: Encourage financing models such as public–private partnerships, concessional loans, and green investment mechanisms to offset the high initial capital requirements of SMR deployment and hybrid system integration that might arise.

Modernise Grid Infrastructure: Upgrade transmission and distribution networks to support variable renewable energy, enhance system flexibility, and ensure reliable integration of SMRs with solar, wind, and storage.

Promote Public Engagement and Awareness: Implement structured stakeholder engagement, public education, and transparent communication initiatives to improve understanding and acceptance of nuclear technology within Ghana's energy transition.

Build Local Capacity and Technical Expertise: Invest in training, research, and professional development programmes to strengthen local capabilities in nuclear engineering, renewable energy technologies, and hybrid energy system operations.

Overall, this study provides a practical and evidence-based pathway for Ghana to implement a reliable, affordable, and low-carbon power system. The findings serve as a strategic guide for policymakers and industry leaders seeking sustainable, long-term solutions for national energy development.

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