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Article

Integrating sustainable wind power into Nigeria's energy system: an analysis of excess electricity, CO_2 emissions reduction, and fuel demand implications

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ABSTRACT

This study explores the integration of sustainable wind power into Nigeria's energy system, focusing on its effects on Excess Electricity Production (CEEP), CO_2 emissions reduction, and fuel demand under different scenarios. Using the Energy PLAN modeling tool, the study evaluates Nigeria's energy infrastructure at an electricity demand of 32 TWh per year, incorporating both onshore and offshore wind power capacities. Three regulatory scenarios are considered: Regulation 1 (heat demand only), Regulation 2 (combined heat and electricity demand), and Regulation 3 (heat pump integration). The results indicate that increasing wind power capacity significantly affects CEEP. At maximum wind penetration, CEEP is reduced by 35% under Regulation 2 with heat pump integration, compared to Regulation 1, highlighting the importance of system flexibility. Integrating heat pumps reduces energy waste and optimizes renewable energy use by 40%. The CO_2 emissions are reduced by about 28% across all scenarios, with the most significant reductions occurring in systems incorporating heat pumps and wind energy. The study shows that primary energy savings were about 25%, driven by decreased reliance on fossil fuels. Wind energy integration leads to a 30% reduction in natural gas consumption, which remains a significant component of Nigeria's energy mix. Sensitivity analysis reveals that variability in wind production and enhanced system flexibility can improve overall energy system efficiency by 20%. The study contributes significantly to the understanding of renewable energy integration in Nigeria, offering a comprehensive framework for incorporating intermittent wind energy sources into the national grid.

1. Introduction

The rapid global population growth and modern industrialization and lifestyles have led to a significant energy demand-supply gap. Addressing this gap requires an urgent expansion of clean, stable, and sustainable energy sources [1,2]. Furthermore, it has been emphasized energy is indispensable for economic growth, social development, poverty alleviation, and national security [3,4]. A consistent energy supply has become critical for nations' development globally. However, the continued dependence on diminishing fossil fuels for energy production has detrimental environmental effects and poses serious health concerns [5,6]. Unfortunately, many developing countries, including Nigeria, still lack stable and reliable energy access to drive their internal economy, thus leading to economic fluctuations and deficits. This energy shortfall impedes practical technological development and reduces agricultural activities, leading to food insecurity. Rapid, ambitious energy generation utilizing all-generation technologies will be imperative for a fast-developing nation like Nigeria [7]. Studies by references [8-11] indicate that approximately 60-70% of the world population, equivalent to 1.2 billion people, still lack access to a modern, steady energy supply, with around 50% residing in sub-Saharan Africa. This situation will worsen in the coming decades if current trends persist, potentially hindering Africa's industrialization and slowing the global transition toward environmental sustainability [12].

Nigeria, the most populous country in the region, has approximately 100 million citizens who lack access to reliable and clean energy [13,14]. This situation underscores the country's severe energy shortages and the urgent need to transition to a more sustainable energy system. Despite being rich in both conventional (non-renewable) energy resources, for example, fossil fuels, and renewable energy sources, like biomass, hydro, solar, and wind, Nigeria possesses enough energy potential to meet the demands of its population. Additionally, it could export surplus energy to neighboring countries, generating revenue. However, the country's current energy supply is insufficient and cannot keep up with the growing demand driven by population growth, industrialization, and increased human activities.

Many countries, including Germany [15], Russia [16], the United States of America [17, 18], and China [19], have transitioned their power generation sectors by increasing the use of lower-carbon fuels like natural gas. In hydrocarbon-dominated economies such as the Gulf Cooperation Council (GCC) countries, such as the United Arab Emirates (UAE), Qatar, Bahrain, and Oman, natural gas is the primary fuel for electricity generation [20]. Around the world, nations deliberately shift from carbon-heavy fuels to natural gas and, ultimately, renewable energy sources. Nigeria is no exception to this trend. Given the current fluctuations in gas supplies and prices of LNG and LPG, which affect the downstream oil and gas sectors [21], along with global trends toward sustainable energy transitions, the need to deploy renewable energy in Nigeria is critical for achieving a transformative shift in its energy demand. Diversifying the energy matrix to include renewable energy will enable the nation to redirect the 'avoided' natural gas to its downstream sector to produce higher-value carbon products. Furthermore, the accompanying decarbonization efforts will contribute to the country's nationally determined contributions (NDCs) under the Paris Agreement.

While renewable energy penetration in Nigeria remains in its nascent stages, it currently utilizes only hydropower and bioenergy as renewable energy sources. However, Nigeria has begun exploring wind and, more prominently, solar PV energy at household and industrial levels to reduce greenhouse gas emissions (GHGs) and carbon footprints [20, 21]. Many countries involved in the Paris Agreement aim to achieve 100 % renewable energy grid power by 2050. In contrast, Nigeria's current renewable energy grid power target remains significantly modest [22]. Nevertheless, transitioning from heavy carbon fuels to lighter and renewable energy is crucial for plummeting GHG emissions and restraining global temperature rises to less than 2°C above preindustrial levels.

This study, therefore, aims to integrate sustainable wind power into Nigeria's energy system by analyzing critical excess electricity, CO_2 emissions, and fuel demand. The specific objectives of this study are: (i) Evaluate the impact of wind power production on Critical Excess Electricity Production (CEEP) and primary energy supply in Nigeria under different regulatory conditions, (ii) Assess the reduction in CO_2 emissions resulting from the integration of wind power into Nigeria's energy mix, alongside the incorporation of flexible energy systems such as heat pumps, (iii) Analyze fuel demand patterns and potential savings under various wind power capacities and regulatory scenarios, aiming to identify optimal energy system configurations and (iv) Develop a systematic framework for integrating fluctuating renewable energy sources (RES) into Nigeria's electricity grid, while minimizing waste and maximizing environmental sustainability.

2. Methodology

2.1 Energy system modeling and scenarios

EnergyPLAN is a computational tool primarily used to evaluate various aspects of energy systems, including Critical Excess Electricity Production (CEEP), CO_2 emissions, Primary Energy Supply (PES), fuel demand, and potential savings. As shown in Figure 1, EnergyPLAN is an energy modeling and forecasting software designed to support the development of national energy planning strategies [23]. EnergyPLAN requires four key input sets for conducting technical analyses, as presented in Figure 2 [24].

After reviewing Nigeria's policies, challenges, and opportunities associated with renewable energy, a baseline model was developed using EnergyPLAN software based on the country's current energy demand and supply data, totaling 32 TWh/year. Considering Nigeria's energy regulatory framework, two system scenarios, Open and Closed systems, were created. Wind power production data, including onshore and offshore capacities, was incorporated into the model, along with system constraints such as heat pump capacities and fluctuating wind production, as adopted from the system software.

The evaluated results were analyzed under three regulatory scenarios to measure the outcome of increased wind power production on key performance metrics. Most of the data input used in this study was sourced from [25-35].

i. Regulation 1 (Heat Demand only)
ii. Regulation 2 (Heat and Electricity Demand)
iii. Regulation 2 + Heat Pump Integration

Furthermore, two National renewable energy adoption (NREA) scenarios were created and analyzed to provide critical insights into system optimization through wind power integration and flexible energy in Nigeria (Table 1). These projected scenarios include NREA30 and NREA50 for analyzing modeled energy scenarios for 2030 and 2050, respectively.

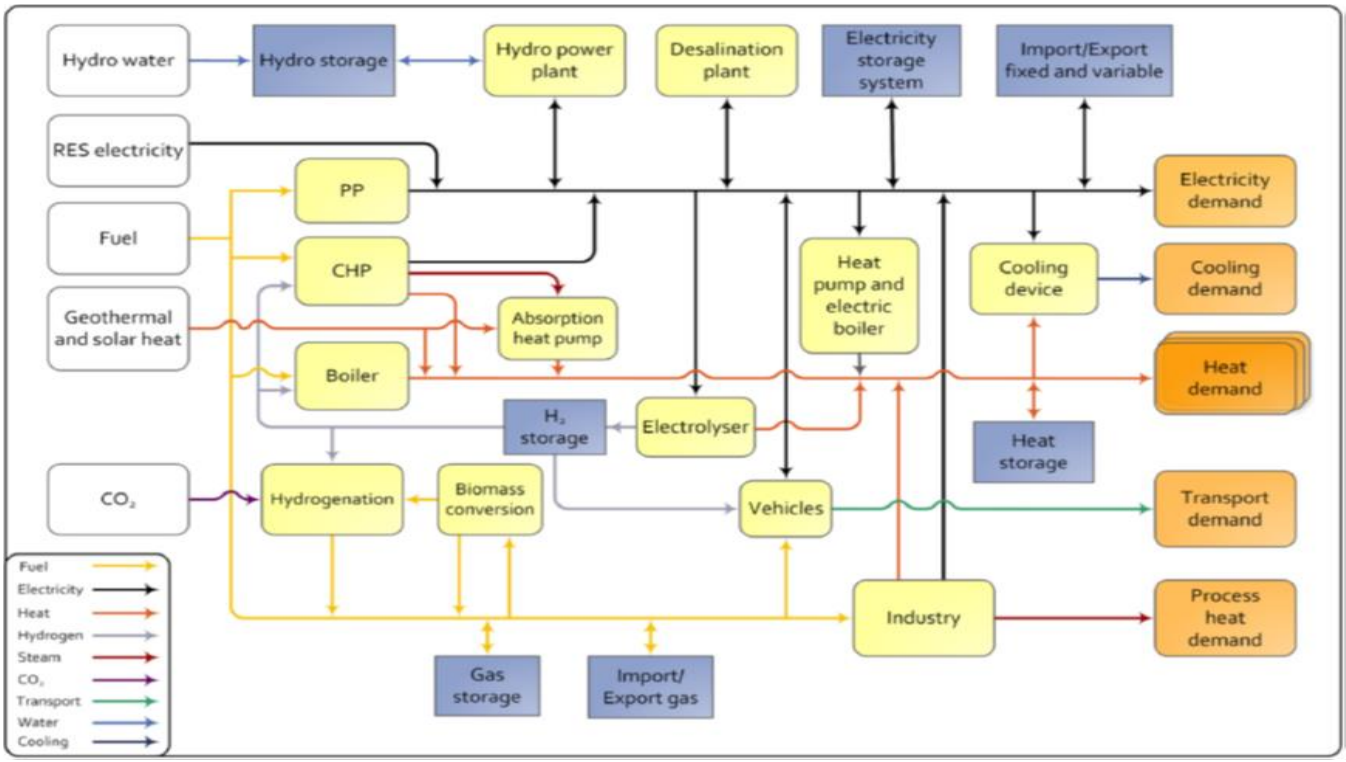

Figure 1. Schematic example of EnergyPLAN pathways [24]

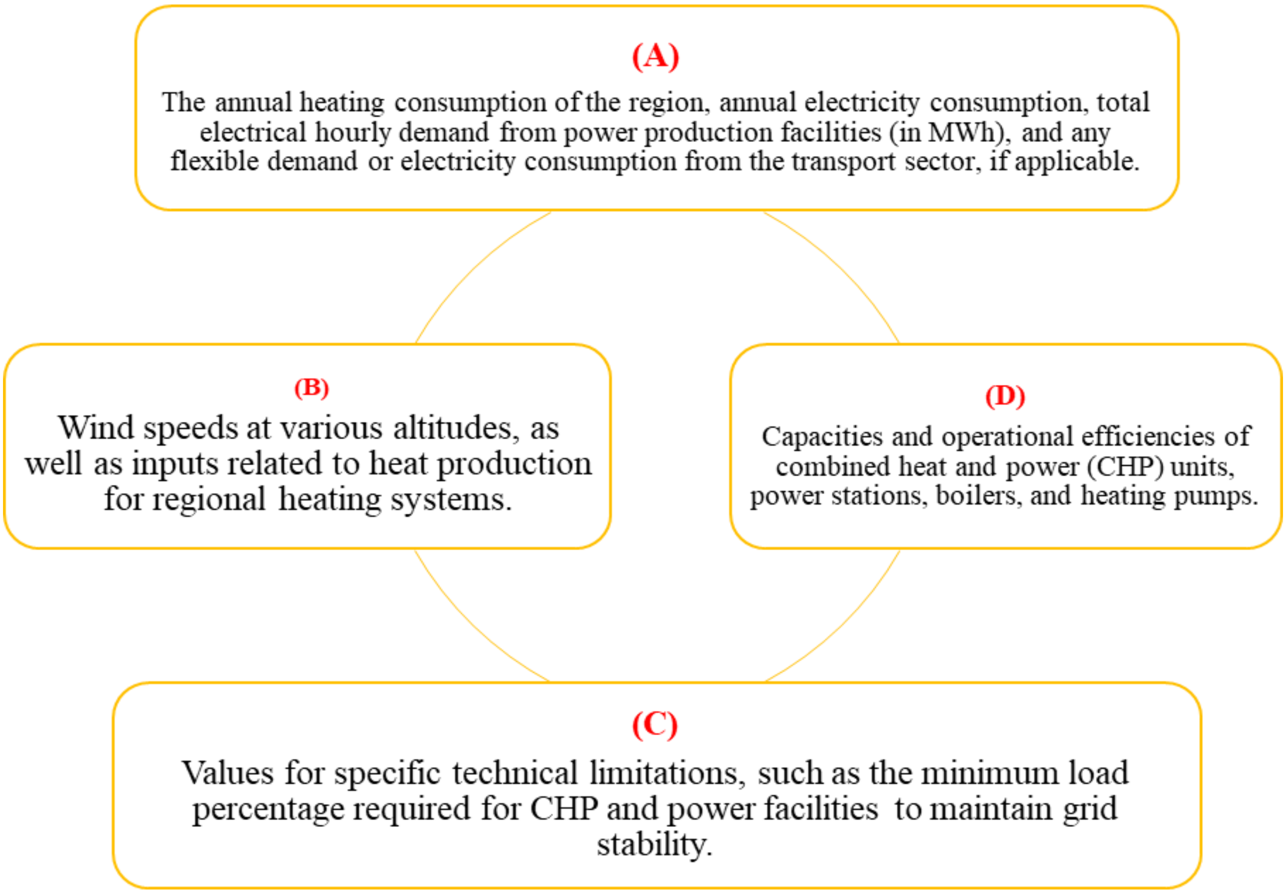

Figure 2. Key inputs for conducting technical analyses in EnergyPLAN Algorithm

Table 1. Assumptions and data for input for the adopted scenarios

S/No	Assumptions	Data
1	Present Energy Demand (TWh/year)	32TWh/year
2	Fuel Price	(NGN500 - NGN600)
3	Expected Wind power production	14.87TWh, including onshore and offshore
4	Variable Wind Production	Between 0 and 50 MW in multiples of 5 MW
5	Onshore/Offshore Wind Capacity in MW	1103MW, and 2206MW
6	Offshore Wind Capacity varied from	2206MW to 6576MW
	Heat Pump Capacity and Heat Pump COP	500Mwe and 3.5

3. Results and discussion

3.1 Overview of results and observations

This study examines the integration of wind power into Nigeria's energy system, focusing on critical excess electricity production (CEEP), CO_2 emissions, and fuel demand under different regulatory frameworks. The results highlight the feasibility of incorporating wind power while optimizing system performance through regulatory strategies, mainly heat pumps. The analysis further reveals the interaction between wind power output and key system performance indicators. However, the Critical Excess Electricity Production (CEEP) depicted in Figure 3, at zero wind production, CEEP is minimal at 0.92 TWh/year under Regulation 1. This indicates a reliance on conventional power sources with limited renewable energy input. CEEP rises progressively with increased wind production, peaking at 42.96 TWh/year at 50 TWh/year wind production.

Under Regulation 2 and Regulation 2 + heat pumps, as depicted in Figure 4, CEEP is reduced to zero across all scenarios, compared to Regulation 1 (Reference regulation), highlighting effective system regulation and energy optimization. The increase in CEEP without regulations underscores the challenge of balancing fluctuating renewable energy sources like wind power. The zero-CEEP under Regulation 2 demonstrates the system's ability to absorb excess electricity through flexible energy solutions, such as integrating heat pumps and modifying heat production [36].

3.2 CO_2 emissions

As depicted in Figure 5, CO_2 emissions decreased from 52.71 Mt/year (no wind production) to 48.8 Mt/year at 50 TWh/year wind production under Regulation 1. Regulation 2 reduces to 43 Mt/year, while Regulation 2 with heat pumps lowers emissions further to 41.42 Mt/year at maximum wind production. This implies that increased wind power production substantially reduces reliance on fossil fuels, directly lowering CO_2 emissions. Also, the enhanced reduction under Regulation 2+ heat pumps demonstrates the synergistic effect of integrating wind power with advanced energy systems. This aligns with global goals of achieving net-zero emissions and highlights the importance of flexible system design in meeting environmental objectives.

3.3 Primary energy supply (PES) and fuel demand

As depicted in Figure 6, PES declines progressively from 248.59 TWh/year (no wind) to 202.72 TWh/year at maximum wind production under Regulation 1, reflecting reduced fossil fuel dependency. Regarding fuel demand, Regulation 2 + heat pumps reduce fuel demand further than Regulation 1, achieving a range of 248.43 TWh/year to 230.25 TWh/year at maximum wind production. The decreased PES and fuel demand indicate enhanced energy efficiency and reduced strain on conventional resources. Given the rising reliance on fossil fuels and the pressing need for renewable energy sources (RES), developing a fuel demand curve demonstrating the percentage utilization of renewable fuels within this study is imperative.

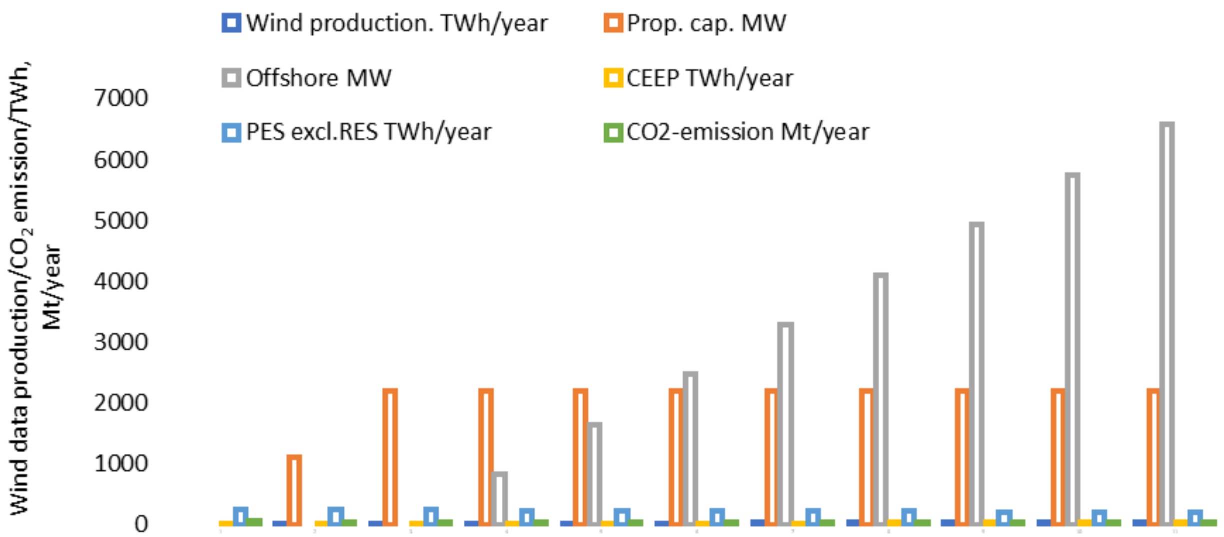

Figure 3. Critical Excess Electricity Production (CEEP) for Regulation 1

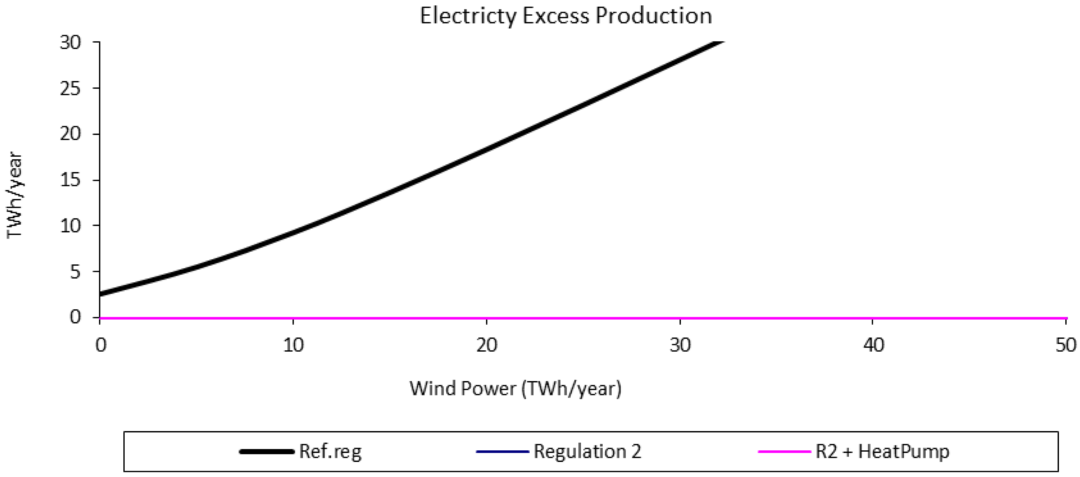

Figure 4. Electricity excess production

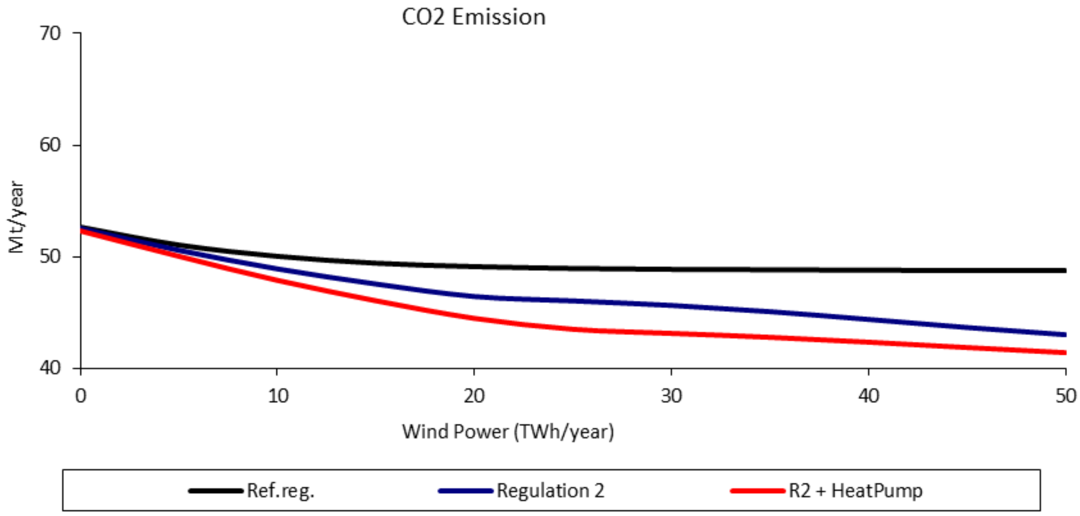

Figure 5. CO_2 emission

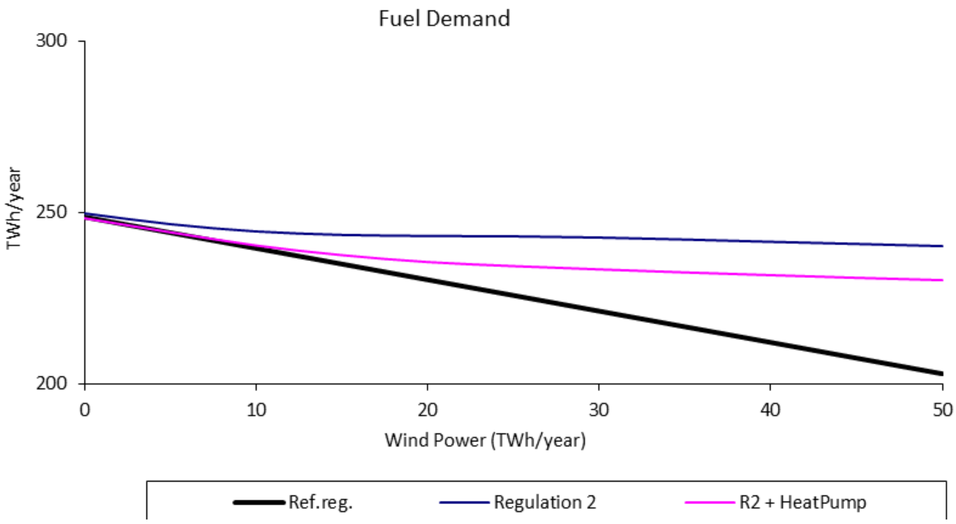

Figure 6. Fuel demand

Our findings unequivocally show that as wind power production varies, fuel demand consistently declines across Regulation 1, Regulation 2, and Regulation 2 with heat pumps, which aligns with the assumptions established. Additionally, with a maximum fuel demand of 250TWh/year, a further inclusion and variation of heat energy will gradually reduce the fuel demand to a critical level of 50-100 TWh/year, thereby achieving a proportionate utilization of the RES. These results highlight the feasibility of transitioning from fossil fuel-based to renewable energy systems while maintaining grid stability and efficiency. Therefore, implementing heat pumps and similar technologies enables better utilization of renewable resources, offering cost-effective and sustainable energy solutions.

3.4 Fuel savings

Fuel savings demonstrate a steady improvement over the modeled periods (2030 and 2050), corresponding to declining fuel demand and increased wind power integration, as depicted in Table 2. Results from the National Renewable Energy Adoption (NREA) scenarios (NREA2030 and NREA2050 scenarios) were compared. Savings of up to 116.41 TWh/year at 50 TWh/year wind production under the NREA2050 scenario underline the long-term benefits of renewable energy investment. Therefore, the fuel savings reflect the economic advantage of RES adoption, reducing operational costs and exposure to volatile fuel prices. Thus, transitioning to wind power and heat pumps represents a strategic investment in long-term energy sustainability for Nigeria.

Table 2. Fuel Savings

Wind prod. (Wh/year)	Wind capacity (MW)	Offshore (MW)	Reference 2030	NREA 2030	NREA 2050 TWh/year
0	0	0	0	-67.5	-142.56
5	1103	0	4.57	-64.51	-138.45
10	2206	0	9.15	-62.51	-134.58
15	2206	822	13.74	-61.58	-131.74
20	2206	1644	18.34	-61.31	-129.64
25	2206	2466	22.93	-61.17	-128.11
30	2206	3288	27.52	-60.62	-126.41
35	2206	4110	32.1	-59.52	-124.37
40	2206	4932	36.69	-57.99	-122.13
45	2206	5754	41.28	-56.16	-119.47

3.5 Projected trends of optimized wind energy utilization

The analysis of modeled energy scenarios for 2030 and 2050 provides critical insights into system optimization through wind power integration and flexible energy investments. Table 3 indicates a complete elimination of CEEP across all renewable energy adoption scenarios for 2030 and 2050. This zero-waste outcome highlights the efficacy of incorporating wind energy alongside flexible system technologies like Combined Heat and Power (CHP) units and heat pumps. Initially, the reference case without wind energy shows CEEP values ranging from 0.92 TWh/year to 42.96 TWh/year as wind production increases to 50 TWh/year. In contrast, all analyzed renewable energy adoption scenarios (NREA) achieve zero excess electricity production. This implies a significant leap in wind energy system utilization efficiency, preventing resource wastage and optimizing the grid's capacity to integrate fluctuating wind energy.

Table 3. Critical electricity excess production trends

Wind prod. (Wh/year)	Wind capacity (MW)	Offshore (MW)	Reference 2030	NREA 2030	NREA 2050 TWh/year
0	0	0	0.92	0	0
5	1103	0	2.64	0	0
10	2206	0	5.58	0	0
15	2206	822	9.32	0	0
20	2206	1644	13.69	0	0
25	2206	2466	18.37	0	0
30	2206	3288	23.2	0	0
35	2206	4110	28.11	0	0
40	2206	4932	33.05	0	0
0	0	0	0.92	0	0

3.6 Fuel demand trends

Table 4 shows a marked reduction, affirming the energy transition benefits of integrating wind power and implementing flexible energy technologies. For the 2030 model year, primary fuel demand drops by 38%, from 248.59 TWh/year in the reference case to 153.52 TWh/year under NREA scenarios. Also, for the 2050 model year, the reduction is even more pronounced, with fuel demand decreasing by 65%, from 248.59 TWh/year in the reference case to 86.94 TWh/year. This improvement highlights the long-term sustainability of wind energy production, reducing dependency on conventional energy sources.

Table 4. Fuel demand trends

Wind prod. (Wh/year)	Wind capacity (MW)	Offshore (MW)	Reference 2030	NREA 2030	NREA2050 TWh/year
0	0	0	248.59	182.12	105.87
5	1103	0	244.02	178.03	102.91
10	2206	0	239.44	173.93	100.62
15	2206	822	234.85	169.85	97.97
20	2206	1644	230.25	165.78	95.05
25	2206	2466	225.66	161.82	92.83
30	2206	3288	221.07	158.62	90.89
35	2206	4110	216.49	156.56	88.75
40	2206	4932	211.9	155.19	87.57
45	2206	5754	207.31	154.2	87.21
50	2206	6576	202.72	153.52	86.94

4. Conclusions

This study demonstrates that integrating wind power into Nigeria's energy system can significantly reduce CO2 emissions and fuel demand while minimizing CEEP under robust regulation. Quantifying these results highlights the practical viability of transitioning to renewable energy. The following conclusions are drawn from the findings:

i. Without regulations, CEEP rises significantly with increased wind power production, underscoring the need for adaptive energy management strategies. Regulation 2 and Regulation 2 + heat pumps successfully reduce CEEP to zero, demonstrating their effectiveness in optimizing energy use and mitigating resource wastage. These results affirm the importance of system flexibility and regulation in harnessing the full potential of renewable energy.

ii. Wind power integration effectively reduces CO_2 emissions, with further reductions achieved through Regulation 2 + heat pumps. This demonstrates a synergistic relationship between renewable energy adoption and advanced energy solutions, aligning with global efforts toward carbon neutrality. The observed decline from 52.71 Mt/year to 41.42 Mt/year under maximum wind power production emphasizes the environmental benefits of the proposed system.

iii. Increasing wind power production reduces reliance on fossil fuels, as reflected in the declining PES values. Including heat pumps further enhances fuel demand efficiency, achieving a critical reduction to sustainable levels. By 2050, the NREA2050 scenario projects fuel demand reductions of up to 65%, highlighting the transformative potential of renewable energy adoption.

iv. Substantial fuel savings were observed, with reductions of up to 116.41 TWh/year under NREA2050 scenarios. These savings highlight the economic advantages of wind energy and the reduced exposure to fuel price volatility. The strategic integration of wind power and heat pumps demonstrates their viability as long-term investments in energy sustainability.

v. Modeled scenarios for 2030 and 2050 reveal progressive improvements in system efficiency, including the complete elimination of CEEP and significant reductions in fuel demand. These trends emphasize the importance of adopting renewable energy and flexible system designs, ensuring Nigeria's resilient and sustainable energy future.

The findings validate the feasibility of transitioning from a fossil fuel-based system to a renewable energy-centric system in Nigeria. Wind energy integration, supported by advanced energy solutions like heat pumps and system optimization for efficient energy supply, offers a pathway to achieving grid stability, economic efficiency, and environmental sustainability.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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