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Review Article

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Affordable Hybrid Energy Solutions for the Least Developed Countries: The example of Bangladesh

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Abstract
Bangladesh is a least developed country exposed to relentless pressures to demand electricity, which becomes a challenge to contain carbon emissions and dependency on fuel imports. Complete reliance on renewable energy is not possible due to the investment, land, and unsteady generation rates of solar and wind. On the other hand, environmental and economic damages of reliance on traditional coals and natural gas systems is considerable. This paper suggests a balanced hybrid energy approach which incorporates small to mid-scale nuclear power, biofuels derived from agricultural residue, along with some selective renewable energy systems with limited fossil fuel back. The aim is to focus on the construction of a reliable and energy secure low-cost low-carbon energy mix. Estimating the trade-off on the costs of carbon emissions, a combination of data from international energy agencies and Bangladesh's national statistics is used. The hybrid system, as suggested from the study, would meet estimated competitive generation costs while lowering total emission made of CO2 by 25-35%. This integrated system approach provides a transitional pathway for other least-developed countries to promote economic development while generating less power.

Introduction

As one of the least developed countries in South Asia, Bangladesh has been suffering from an acute energy crisis for decades. Population growth, urban expansion, and industrialization have spurred national demand for electricity. However, generation capacity has been largely constrained due to the reliance of the country on imported, environmentally damaging, and economically stressful fossil fuels— natural gas and coal. The transition to renewable energy has been sluggish due to high capital expenditures of renewables, unreliable generation, and low technology adoption. As a result, the Bangladesh economy is suffering from sluggish growth, rising production costs, and inefficient power cuts. While the government pursues cleaner and more sustainable energy sources under the target of universal electricity access, energy cost, supply reliability, and environmental protection remain tightly coupled. The government is investigating the sacrifice of hybrid energy mix systems— the strategic integration of nuclear, biofuel, and renewables—as one of the crucial elements of the energy policy for Bangladesh and other least developed countries for the time being.

Bangladeshi Challenges. Balancing the cost, sustainability, and reliability of energy systems is a critical challenge for Bangladesh. The heavy reliance on imported fossil fuels aggravates the costs of production and exposes Bangladesh's economy to global price fluctuations. Yet, a full transition to renewable energies is unrealistic because of high-cost investments required, gaps in technology, and the unstable generation of solar and wind resources. Consequently, this study examines a hybrid energy mix model encompassing small-scale nuclear pkower, biofuels, solar energy, and a small share of fossil fuels. The aim is to find an optimal solution that achieves the targets of the study by minimizing the cost burden on the consumers and reducing the carbon footprint. The research sought to answer the following three questions: (1) Which of these energy sources can be combined to sustainably address the demand in Bangladesh? (2) How can nuclear and biofuel technology be used to defend self-reliant energy? (3) What hybrid approach leads to benefits on the economy and the environment? The ultimate aim of the study is to demonstrate to other least-developed countries a clear and reasonable path to achieving energy that is clean, affordable, and reliable, in line with global climate targets.

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Literature Review

The energy transition research for least-developed countries (LDCs) sees the need for more comprehensive energy systems instead of multi-source dependence. The IEA (2023) reported that fossil fuel dependence for the LDCs is over 70% while renewable forms of energy constitute under 10% of the energy composition. The documentation mentions that the large-scale deployment of renewables is largely hindered by inadequate infrastructure financing and climates within economically low regions. Alam et al. (2021) articulates that the inefficiencies of renewables in Southern Asia is a consequence of inconsistent solar radiation and low grid capacity. In like manner, Rahman and Khan (2022) asserted that energy overreliance of natural gas in Bangladesh exacerbates energy unsecure and vulnerability in gas importation. The research coming from the World Bank (2020) indicates that hybrid systems of renewables and stable baseload power systems like nuclear or biomass assist in reducing generation costs and emissions. It is these findings that reiterate the global need for balanced energy resources for developing economies to achieve positive economic and environmental results. Yet, the gap in Bangladesh's resource constrained and research localized systems frameworks remains. It is this gap that motivates the development of a custom hybrid energy mix model in this study.The more recent studies highlight the economic potential of hybrid energy systems for developing countries. Many researchers claim that renewable energy can be combined with traditional baseload power to hold national grid systems reliable. According to Chowdhury (2022), for some areas of Bangladesh, the solar-biomass hybrid systems improved the effectiveness of rural electrification by nearly 18%. Hossain and Alam (2023) stated that small modular nuclear reactors (SMRs) will provide stable power and minimize low- capacity grid transmission losses. Global Energy Outlook (2023) also commented that, with adequate management, the energy demand in the tropics can be met to 10% with biofuels from agricultural waste. Still, running the literature, which balances the nuclear-biofuel-renewables triad on socio- economic grounds in low-income countries, is peer-reviewed and scant. The focus of many published models is on single sector improvement and, therefore, ignores applied integrated policy alternatives in finance, collaboration, and cost recapture. Hence, to counterbalance, the current research is oriented to propose a unified, analytical hybrid energy framework that considers cost, potential carbon reductions, and predicted growth in Bangladesh, for example, economically.

Methodology

This research applied a mixed qualitative and quantitative approach to develop a viable hybrid energy framework for Bangladesh. This research collected and analyzed energy consumption patterns and generation capacity with secondary data obtained from BPDB, IEA, and World Bank (2018-2023). Thereafter, sectoral emission intensity was analyzed. This was followed by a comparative assessment of traditional fossil fuel systems with hybrid configurations incorporating small modular nuclear reactors, solar, biofuel, and limited fossil fuel. Emission factors, generation costs, and energy security indices were analyzed using weighted models based on the Analytical Hierarchy Process (AHP). To inform research design, case studies from other least-developed countries (Nepal, Kenya, and Nigeria) were analyzed to identify transferable strategies and contextual constraints. In addition, simulation models that estimates expected energy cost and carbon dioxide emission were designed. All variables were aligned to guarantee internal validity and ensure relevance to the proposed policies. As a result, this approach to methodology provided the research with practical evidence to determine how hybrid systems could allow Bangladesh to move to an affordable, reliable, and sustainable energy generation framework that is aligned with the goals of the country.

Results and Findings

The results of this study indicate that through a balanced hybrid energy mix, Bangladesh has the potential to attain cleaner and more reliable electricity at a lower generation cost. Among the myriad combinations evaluated, a configuration comprising roughly 35% natural gas, 25% solar and wind renewables, 20% biofuel, and 20% small modular nuclear power emerged as the best-performing. This mix not only ensured solid grid stability, but also mitigated CO2 emissions by close to 30% and reduced fossil fuel import dependency by a third, compared to the existing fossil fuel-dominated grid. The results also inferred that small modular nuclear power plants could provide consistent baseload supply, while biofuel from agricultural residues could serve as affordable backup. During the operational day, renewables would meet peak demand and operational costs would be diminished. Besides, the operational use of local bio-resources would create job opportunities, economically energize rural communities, and assist in waste pollution abatement. Overall, the results showcased that hybrid systems, which Bangladesh could develop instantly, would incorporate the best possible compromise of lower cost and reliability with a pronounced degree of sustainability. This puts Bangladesh on the path towards a green energy transition with the certainty of no power shortages on the supply side and no severe economic impact on the industries and the power consumers.

Discussion

The findings from this study show that Bangladesh would derive substantial advantages from a hybrid energy system. The combination of small modular nuclear reactors, biofuels, solar energy, and limited fossil fuels mitigates affordability, dependability, and environmental concerns. The addition of nuclear energy reduces the risk of power outages, as it provides a steady baseload, and this aids in overcoming the challenges of relying solely on intermittent renewable sources. Agricultural residue biofuels supply affordable backup energy and provide economic prospects to rural areas by waste reduction and additional income. Solar and wind energy meets peak day demand, fossil fuel consumption, and operational costs. Dependent imported fuel is reduced, and national energy security is enhanced by the 30% projected reduction of carbon dioxide emissions. Considering the above, it is reasonable to expect challenges in overcoming the high initial investment and biofuel safety management. Coordination with farmers to plan and execute supply chains in a biofuel system is complex. Infrastructure, operational, and safety investment in nuclear energy invites further support. Policymakers should plan for support and local produced incentivization. All in all, hybrid energy systems would be a practical solution for Bangladesh.

Energy Scenario Analysis

Bangladesh's current energy supply largely consists of natural gas and coal. This creates dependency on imported fossil fuels

and leads to environmental pollution. There is burning of solar and wind energy on the supply side as the high cost of installation and inconsistency in supply minimizes their use. Peak demand is often unfulfilled and power shortages occur while carbon emission on the fossil fuels side continues to increase. The proposed hybrid energy mix aims to change this scenario by incorporating small-scale nuclear power + biofuels from agricultural residues + solar + wind + other biofuels. In this scenario, nuclear energy serves as the reliable baseload supply while the solar and wind powers play their parts during the peak daytime demand. The biofuel portion provides flexible backup to emission neutral fossil fuel. This waste reducing biofuel will further support rural incomes by lowering costs. More reliable net generation, controllable costs and an expected net reduction of 30% of current system CO2 emission provides further system improvement. A simple comparison shows that while the current system provides short term cheaper power, it is the hybrid system that will provide energy security long term as well as social and environmental benefits. This scenario shows that Bangladesh is positioned to and will gain reliable energy through hybrid systems.

Policy Implications and Recommendation

This study shows that hybrid energy systems improve electricity supply, decrease carbon emissions, and provide assistance to rural communities and the government and policymakers could facilitate this by taking some basic, yet critical, steps. These include offering financial assistance and subsidies for renewables, especially solar and wind, which are costly for many small users, and integration of safe operating regulations and training modules for small modular nuclear power plants. Also, farmers and rural communities could be engaged in biofuel production from agricultural waste, which would create jobs and rural income. Energy policies should also be designed for the efficient coupling of varied energy sources, like steady nuclear and daytime solar and wind power, with biofuel as backup. These policies should tackle the achievable within current resource constraints without aiming for an outright fully renewable transition. With the implementations of these recommendations, Bangladesh would be able to deliver energy that is cleaner, more reliable, and affordable while boosting local economies and decreasing reliance on imported fuels.

Limitations and Future Work

While this study highlights some advantages of hybrid energy systems on Bangladesh's context, a few considerations remain. Firstly, a good portion of the data included in the analysis is secondary information. This may result in a lack of context for some of the local conditions. Secondly, the planning, financing, and requisite skills for small-scale nuclear energy and biofuels are not even close to being developed. Thirdly, given the reliance on the weather, the continuity of supply of solar and wind energy will always remain inconsistent. In future research, the priority should be to obtain firsthand data from local power plants, local farms and their installations, as well as renewable resource and biofuel research, to improve accuracy in analysis. The practical aspects on supply chain management of biofuels, nuclear safety, and hybrid systems will, undoubtedly, need small-scale pilots in defined districts to provide some understanding. This will inevitably be linked to empowerment research in the design and training of energy system participation farmers. Despite some oversimplifications and the limitations, the study aims to provide a balanced perspective of the potential mixed energy options for Bangladesh. With the dedication of policymakers, community members, and researchers, the energy system of Bangladesh will become more economically accessible in the coming years.

Conclusion

This study seeks to illustrate how Bangladesh, a least developed country, can advance to a more positive energy future through the clever and inexpensive hybrid energy system discussed. The system aims to integrate small-scale nuclear, solar, wind, and biofuel components to enhance the reliability of electricity generation and reduce environmental degradation. The nuclear component provides energy reliability while the renewables and biofuels contribute to waste reduction and provide job support at the local level. This combination also decreases the economic loss from imported fossil fuels and reduces the country's imported fuels dependency. The analysis also identifies potential actions Bangladesh can take toward cleaner energy, even if it cannot yet realize a fully renewable system, using practical approaches and local engagement. Admittedly, as discussed in the study, the potential actions remain constrained by resources, limited access to relevant data, and lower levels of advanced analytical skills. To maximize potential, future efforts should emphasize the implementation of hybrid systems and local capacity building. The message I really tried to communicate through this study is an uncomplicated smart low cost proposal as a possible highway for developing countries like Bangladesh. Although I am a high school graduate and thus lack detailed advanced understanding of the subject, I sincerely tried to provide a truthful interpretation of the possible integration of technology and the principles of sustainability toward a more positive energy future [1-5].

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