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Integrating Renewables Into Stand-alone Hybrid Energy System and Meeting Freshwater Demand by Utilizing Excess Energy

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Abstract

Hybrid renewable energy systems, well-known for their ability to use multiple renewable sources parallelly to supply power, generate significant energy excess to demand. This study optimizes a standalone hybrid renewable energy system (HRES) for Rangabali Upazila, Bangladesh, integrating PV, wind turbines, a diesel generator, and either pumped-hydro storage (PHS) or batteries. The system addresses electricity demand and freshwater production using excess energy. Simulations in HOMER Pro indicate that PHS outperforms battery storage in both economic and environmental aspects. Systems with PHS achieve a net present cost (NPC) of $28.33M and a cost of energy (COE) of $0.175/kWh in both load-following and cycle-charging strategies, compared to $33.57M NPC and $0.207/kWh COE for the systems with battery. Additionally, PHS systems achieve zero emission as they do not require diesel generator operation, while battery systems consume up to 415 L of fuel and emit 1098 kg of CO_2 annually. The results demonstrate that the proposed systems ensure reliable power and freshwater supply, contributing to sustainable development in remote regions.

Keywords: Cost of energy, emission, freshwater, renewable energy, utilization of excess energy

1. Introduction

In recent years, global energy demand has increased considerably. The rising need for energy is due to population growth, industrial expansion, and technological reliance. This need is especially high in developing countries like Bangladesh, where there is an immediate need for reliable, economical, and environmentally sustainable energy solutions. Around 97% of the electricity produced in Bangladesh comes from non-renewable energy sources like natural gas and diesel/petrol. Again, energy consumption to supply ratio has been increasing rapidly.[1] In recent years, Bangladesh has achieved economic growth exceeding 7%. The government has set targets to boost electricity production, aiming to reach 40,000 megawatts by 2030 and 60,000 megawatts by 2041 to sustain expanding sectors.[2] Also, the produced electricity is only available for 90 % of the total population. As we rely on conventional fossil fuels, this leads to increasing energy costs and contributes heavily to environmental degradation, which increases greenhouse gas emissions. On the other hand, renewable energy sources are neat, but the uncertainties of power generation make these less effective for a wide use case. [3] This has opened a new door for a much more environment friendly and reliable system of energy generation called hybrid energy system or HES that integrates renewable sources like solar energy, wind energy, hydro power etc. Further developments in technologies of hybrid energy system will enhance both economic and technical aspects. For example, combining combustion engines or batteries with PV-based systems has been shown to be a good investment.[4], [5], [6]

Again, there is an adequate amount of surplus energy that is generated from the hybrid energy system. This excess energy can be used to supply freshwater, specially in island areas where scarcity of freshwater is a major concern. Many researches have been done based on the optimization methods for the HRES system to meet the community and the ROD (Reverse osmosis desalination) load requirement. In this respect, Kyriakarakos et al. [7] applied particle swarm optimization (PSO) to optimize PV/Batt/RO system to meet the load demand for the 200 m^3 freshwater production. Zhang et al. [8] used simulated annealing-chaotic search algorithm for the PV/ WT/Batt-based ROD system. Gokcek [9] designed a PV/WT/Batt/DG system using the HOMER Pro to meet the load demand for the ROD fresh water production in Turkey and the result suggested a COE of 0.308/$kWh in the off-grid areas. A. Jaman et al.[2] designed a system with PV/WT/BG/FC/electrolyzer/HS/VRF battery to meet community load that exhibits an ideal energy cost of 0.1393$/kWh, carbon emissions amounting to 184283.1 kg CO2-eq/yr. Given Bangladesh's increasing energy needs along with limited electricity access in rural and remote areas, there is a promising opportunity for implementing standalone hybrid energy systems and meeting the local energy demands. A system comprised of photovoltaic (PV) system and wind turbines can be implemented. This system setup has significantly contributed to lowering the cost of energy (COE) and net present cost (NPC) while reducing the environmental impact. Hybrid systems contain dispatch strategies that regulates the generators and batteries when there is shortage of renewable energy to meet the demand for electricity. It has significant influence on the life-cycle cost by influencing fuel consumption and battery life span. [10]

In this study, a hybrid energy system is designed, based on economic and environmental aspects, to meet the requirement of community load and ROD load for fresh water supply. A comparative analysis of battery and pump-hydro system (PHS) options for a HES to meet a similar dynamic load profile is also conducted. The study examines the effects of dispatch strategies and different uncertainties of climatic data, load profile, hardware component's costs and performance on the NPC, COE.

2. Site Selection

This study aims to provide an optimum hybrid renewable energy system (HRES) configuration for Rangabali Upazila (Latitude:21° 56′ 0″ N, Longitude: 90° 26′ 0″ E), Patuakhali district in Barishal division, a remote coastal region in Bangladesh. It is an off-grid, rural, underdeveloped region in Bangladesh. A power substation has been set up recently in Rangabali upazila in Patuakhali district.

The study area is blessed with adequate and admirable amount of solar irradiance and wind speed throughout the year. So, solar and wind have been considered to be the primary sources of renewable energy. Solar irradiance and wind speed data at 50 meters range for 5 years (2018-2022) are acquired from NASA Data Access Viewer [11] which are reported in **Fig. 2** and **Fig. 3**.

The average solar irradiation and the clearness index is 4.65 kWh/m^2 /day and 0.508, respectively. The months with the most solar radiation are February, March, April and May, when average solar irradiance exceeds 5 kWh/m^2 /day. Average wind speed at the study area is 5.09 m/s at 50 meters. The windiest months in the area are February, July, August, September and October.

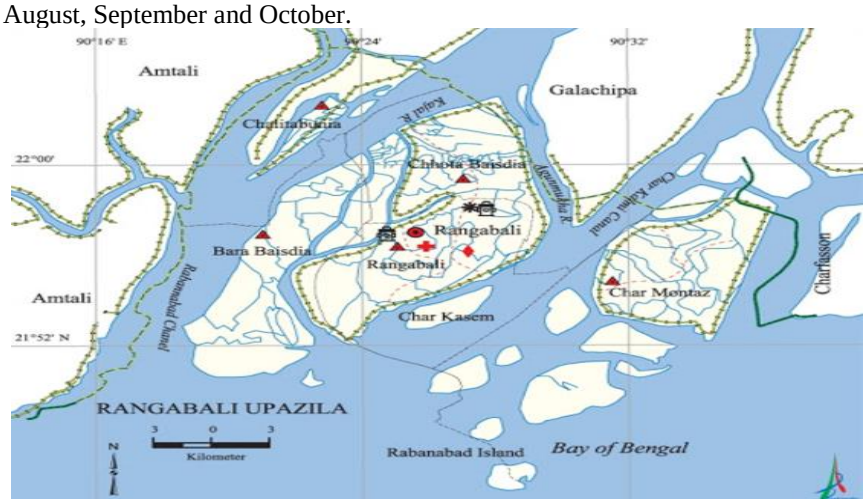


Fig. 1. Location of Rangabali Upazilla (Latitude:21° 56′ 0″ N, Longitude: 90° 26′ 0″ E)

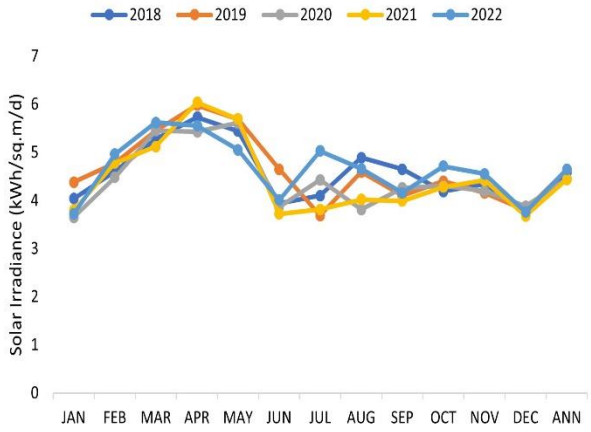


Fig. 2. Solar irradiance profile

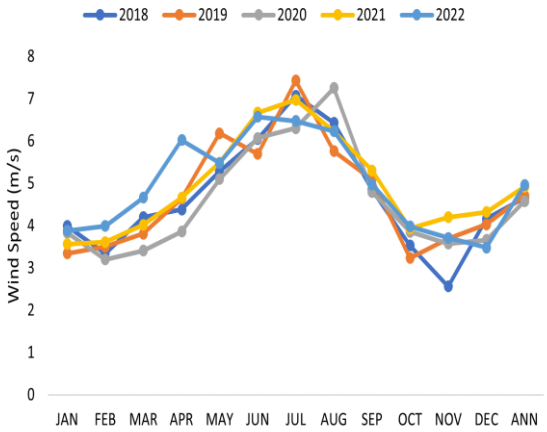


Fig. 3. Wind speed profile at 50 meters

3. System Configuration

Two different hybrid energy systems are considered in the study that incorporate solar and wind as the renewable energy sources. Diesel generator is considered as back-up source when there is power shortage. PV, wind turbine (WT), converter, diesel generator (DG) are the common components in both systems, whereas battery and pump-hydro storage system (PHS) create distinction between two systems.

- **System A**: PV, WT, DG, convertor, pump-hydro storage system
- **System B**: PV, DG, convertor, battery integrated system
- **Dispatch Strategies**: Load following (LF) and Cycle charging (CC)

PV module: Monocrystalline PV module is considered in the study that can convert only 15–20 % of the incident solar irradiation on it.[12], [13], [14]
Wind turbine: The systems are equipped with Vestas V47 wind turbine that has a capacity of 660 kW. It has a cut in speed of 4 m/s and cut-out speed of 25 m/s. It is considered on the basis of excellent and admirable wind speed that is available throughout the year. [15]
Battery: Li-ion battery with capacity of 3.6 kWh is considered that has a lifetime of 15 years. [16]
Pump-hydro storage system (PHS): Pump-hydro storage system is considered that has a difference of 100 meters between upper and lower reservoirs and it can store a large amount of energy equivalent to 22 kW.[17]
Diesel generator: Diesel generator in the system is of 45 kW capacity.[16] The assumed fuel price is 0.9$/L.

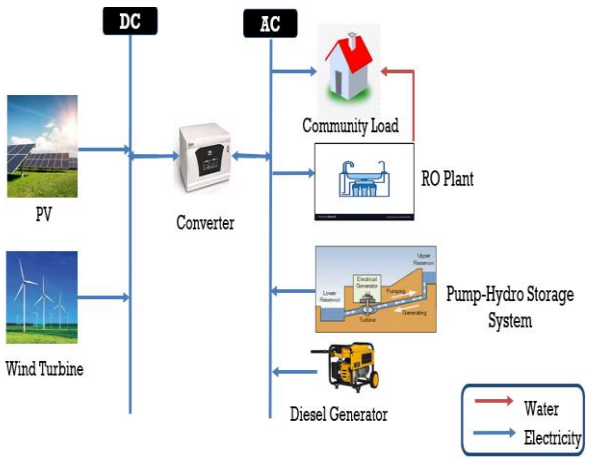


Fig. 4. PV/WT/DG/PHS system

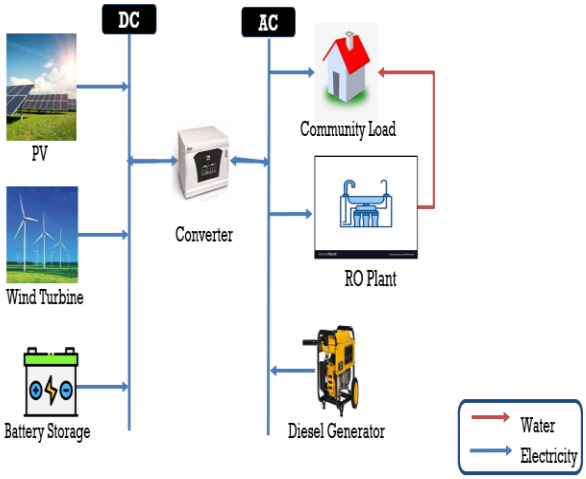


Fig. 5. PV/WT/DG/BAT system

Table 1. Technical characteristics and economic data for HES components [16], [18], [19]

Components	Description	Capital Cost ($)	Replacement Cost ($)	O&M Cost ($)	Lifetime
PV	400 W	440	320	20	25y
WT	660 kW	124000	124000	500	20y
DG	45 kW	13,300	10,000	0.050	15,000h
Converter	1 kW	300	300	0	15y
PHS	22 kW	22000	22000	100	40y
Battery	3.6 kWh	672	400	10	15y

4. Result and discussion

The results from the simulations show a clear difference between the two systems (pumped-hydro system and battery) in terms of economic performance both in load following (LF) and cycle charging (CC) strategies. Net present cost (NPC) and levelized cost of energy (LCOE) are considered as economic parameters in this study. The NPC for the systems with PHS is significantly lower than that of systems with battery. The systems with PHS have NPCs with the value of 28.330 $M for both CC and LF; whereas systems with battery storage have NPCs of 33,574 $M (LF) and 33,578 $M (CC). Similar scenario is seen in case of LCOE. For PHS, the COE is 0.1749 $/kWh in both load following (LF) and cycle charging (CC) modes. However, for the battery system, the COE is higher, at 0.207 $/kWh for both LF and CC modes. This indicates that PHS provides a more cost-effective solution in terms of capital investment and long-term economic viability and also electricity generation at a lower cost compared to the battery system.

PHS systems do not consume any fuel as they do not have the necessity to run diesel generator due to higher storage capacity of PHS. On the other hand, systems with battery require a significant amount of diesel fuel and produce CO_2 as a consequence. In load following mode, battery system consumes 95 L fuel and produces 251 kg CO_2 per year. And in cycle charging mode, battery system consumes 415 L fuel and produces 1098 kg CO_2 per year. This exhibits that systems with PHS have significant environmental advantage over systems with battery in addition to economic aspects.

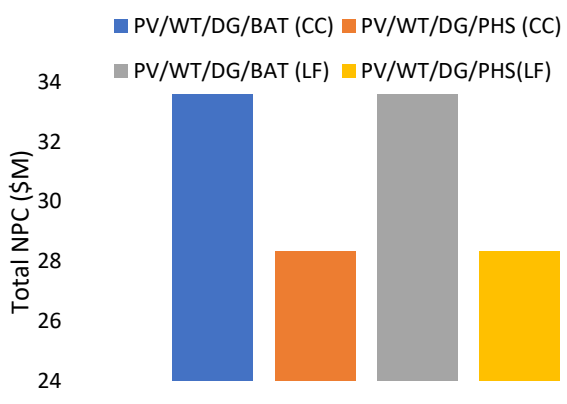


Fig. 6. Total Net Present Cost

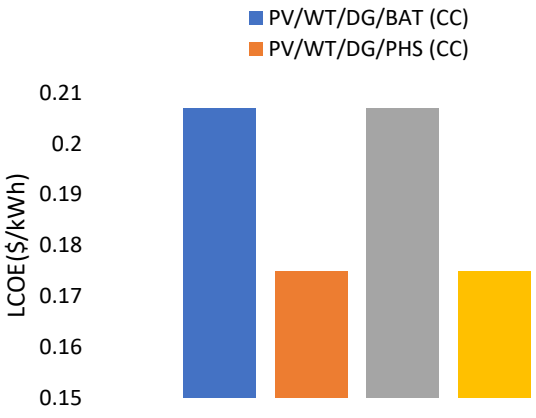


Fig. 7. Levelized Cost of Energy

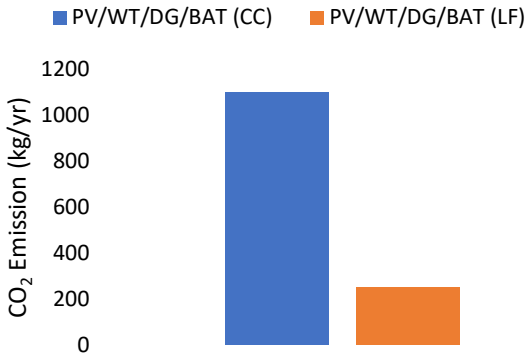


Fig. 8. CO_2 emission

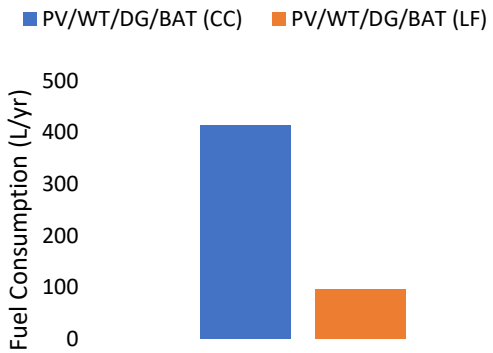


Fig. 9. Fuel consumption

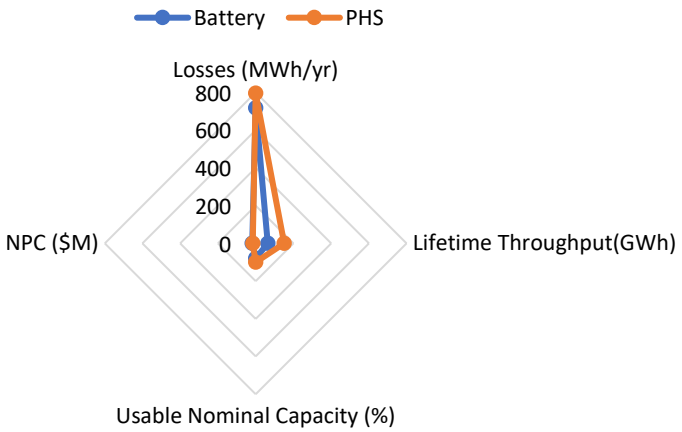


Fig. 8. Comparison between battery and PHS

Comparison between Battery and PHS

In comparing the two storage systems, it is clear that PHS provides a more cost-effective solution in terms of NPC and COE, making it a better choice for economic feasibility. However, the battery system outperforms PHS in terms of environmental sustainability, with significantly lower CO_2 emissions and fuel consumption. But PHS based system has further advantages due to higher usable nominal capacity and lifetime throughput and lower energy losses with zero storage depletion. Net present cost for pumped-hydro system (15.6$M) is significantly lower than that of battery storage (18.3$M). Again, PHS system has a lifetime throughput of 151 GWh with a usable nominal capacity of 100%, significantly higher than 64 GWh of battery system with 80% usable nominal capacity. But, with lower energy losses, losing 718 MWh per year compared to the loss of PHS system (96 MWh/year), battery system outperforms battery system in case energy storage. Still advantages make PHS more reliable for meeting energy demands, especially when energy generation is not uniform.

5. Conclusion

In this study, different configurations of hybrid energy system with different dispatch strategies are analyzed and optimized to meet the community load and ROD load for freshwater. PV/WT/DG/PHS and PV/WT/DG/Battery are the optimized system configurations, which are optimized in both in load following (LF) and cycle charging (CC) modes as dispatch strategies. The results display that system configuration containing pump-hydro system (PHS) is a more cost-effective and sustainable than the system with batteries, in both LF and CC. System with PHS offers lower net present cost (NPC) and levelized cost of energy (LCOE). Also, CO_2 emission follows the similar trend, since systems with PHS have larger capacity with 100% usable nominal capacity. Again, battery and PHS are compared on the basis of energy loss per year, lifetime throughput and usable nominal capacity. In

all the aspects mentioned above, PHS outperforms battery. Moreover, higher lifespan and zero chemical composition give PHS an edge over the battery.

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