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Integrating Supercapacitors and Redox-Flow Batteries for Enhanced Energy Storage in Off-Grid Solar/Wind Hybrid Systems

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Abstract

Fossil fuel-based power plants contribute significantly to rising greenhouse gas emissions, which have a negative influence on climate change, global temperature, and human health. This circumstance leads to the use of renewable energy sources. Because of the global energy crisis and the restricted availability of conventional fuels in some locations, the usage of renewable energy resources is crucial for sustainable development. However, renewable energy resources are mostly fluctuating along with their immoderate cost pose major challenges to the implementation of renewable energy. To deal with these problems, a hybrid renewable energy system that combines numerous sources with energy storage has been created as a durable and effective solution. This study describes a collaborative and conceptual approach to the design of an off-grid solar/wind hybrid renewable energy system that includes a hybrid energy storage system made up of a redox-flow battery and a supercapacitor. The existing literature does not cover the simultaneous integration of renewable energy sources and hybrid energy storage systems. HOMER software has been used in this study to estimate load requirements which predicts the most economical combination costs $35,630 and generates 1.88KW power per day as well as evaluating the microgrid system's techno-economic and environmental performance.

Keywords: Hybrid renewable energy, Energy storage, Redox-flow battery, Supercapacitor, HOMER software

1. INTRODUCTION

Because of urbanization and industrialization, the twenty-first century has become a difficult as well as challenging period as high energy consumption is a major issue[1]. Globally, around 1.3 billion people lack access to electricity, with 80% of them living in rural areas[2]. Expanding grid supplies to rural off-grid villages is difficult due to location and cost constraints. In Bangladesh, approximately 80% of population lives in rural areas. The government of Bangladesh is under great social, economic, as well as political pressure to solve the electricity issue[3]. Although over 98% of power is generated by conventional non-renewable sources, the expense of imported fuels forces the government to enforce schedule load shedding. Furthermore, the usage of fossil fuels, which are non-renewable sources of electricity generation, is increasing CO_2 emissions globally[4], [5]. Owing to this, using renewable resources like solar energy and wind speed to satisfy constraints such as higher power consumption and lower emissions has become a viable approach. Moreover, utilizing these energy sources as a hybrid energy system will be more beneficial. Although using renewable energy sources in a hybrid system could be beneficial and high demanding but the variability and uncertainty of these power generation sources restrict supply demand balancing[6]. The synchronization of electricity generation and utilization is one the major responsibilities as well which has to be maintained properly by the operators. The notion of self-sufficiency refers to the use of electrical energy generated at the same area where it is utilized, either immediately or through storage systems. Combining renewable power with storage technologies like batteries and supercapacitors can dramatically boost self-sufficiency[7], [8]. This paper aims to identify the optimal system size capable of meeting a primary load requirement of 120 kWh per day, serving approximately 357 households in Gomatoli, a site located in Cox's Bazar. The study employs a straightforward yet effective method for sizing and analyzing the hybrid energy system (HES) through the use of the software HOMER (Hybrid Optimization Model for Electric Renewables). The main objective is to design a reliable and cost-efficient hybrid energy system. The site is located between latitude 21°24.8' N and longitude 91°59.4' E, is ideally positioned for harnessing solar irradiation as well as wind

speed which is very accurate to produce solar and wind energy respectively[9]. The monthly solar irradiation ranges from 4.041 to 5.878 KW/m^2/day and wind speed ranges from 6.750 m/s to 3.960 m/s. **Fig. 1** depicts the proposed hybrid energy system which will generate electricity using the power generation and storage systems for 357 households.

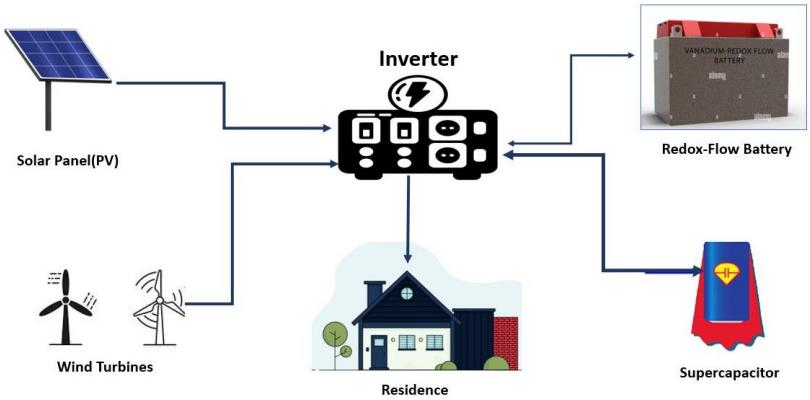


Fig. 1. Hybrid energy system model

The novelty of this research is that it introduces a unique hybrid renewable energy system that combines solar and wind power with an innovative energy storage solution using redox flow batteries and supercapacitors. These storage technologies, which have not been previously integrated in similar studies, provide enhanced controllability and adaptability. The system's performance was evaluated using HOMER software, demonstrating a cost-efficient design with significant environmental benefits, paving the way for a more reliable and sustainable energy future.

2. SYSTEM DESIGN & CONFIGURATION

This renewable hybrid energy system integrates solar photovoltaic (PV) panels and wind turbines as the primary power generation sources as well as combined with supercapacitors and redox flow batteries for energy storage with an inverter which has been depicted in Fig. 1 . The system is configured to ensure a reliable and efficient energy supply to meet the energy demands of the target off grid area.

2.1. Power generation system

The main sources of power generation are solar and wind for this off-grid system in this selected region, and for this, solar PV panels and wind turbines have been used in this case so that energy can be generated efficiently from these sources with the minimum amount of loss. The solar panels use the radiation of the sun and convert it into direct current (DC), while the wind turbines harness kinetic energy from the wind to generate alternating current (AC) electricity.

Solar PV: The direct conversion of sunlight into electricity, involving no heat engine occurs in photovoltaic conversion. A photovoltaic power-generating device has a durable and simple design, consisting of many components such as cells, electrical as well as mechanical connections and mountings, and means of controlling and modifying the electrical output. This type of device requires little maintenance, and its main advantage is that it is built as a stand-alone system capable of producing outputs ranging from microwatts to megawatts. The rating of these type of systems are in peak kilowatts, which is the quantity of electricity that a system is expected to produce on a clear day with the sun straight overhead[10]. The specifications of solar PV has been listed in Table 1.

Table 1. Specifications of solar PV

Specifications	Value/type
Panel type	Flat plate
Nominal capacity	327W
Temperature coefficient	-0.386
Operating temperature	46°C
Efficiency at STC	13%
Nameplate current/voltage	6.46 A/65.10 V
Derating Factor	85%
Lifetime	25 years

Wind Turbine System: Today, the importance of wind energy cannot be ignored, and around the world, the rapid advancement of wind energy technology is increasing. Wind energy has a 3000-year history. Wind energy conversion systems can be classified as either aerodynamic drag- or aerodynamic lift-based. Aerodynamic lift is used in modern wind turbines and lift devices use airfoils to interact with the incoming wind. The output of the wind turbine is converted into DC current using a rectifier so that it can be integrated with the other power generation systems[11]. The specifications of the wind turbine model have been listed in Table 2.

Table 2. Specifications of wind turbine

Specifications	Value/type
Rated Capacity	6 KW
Cut-in wind speed	4 m/s
Cut-off wind speed	21 m/s
Rated wind speed	11 m/s
Hub height	30 m
Rotor Diameter	5 m
Lifetime	20 years

2.2. Energy Storage System

The power that is generated by the solar PV and wind turbine will be stored by an arrangement of supercapacitor and battery.

Supercapacitors: Supercapacitors are modified versions of capacitors which have more energy density, power density as well as cycle life than normal capacitors. There are basically three types of supercapacitors available. They are EDLCs (**Electric double-layer capacitors**), hybrid capacitors and pseudo-capacitors. A supercapacitor charges and discharges in 1-30s, which is substantially faster than a standard battery. A battery takes nearly 5 hours or more to fully charge itself, which is slower than a supercapacitor. Moreover, the life cycle period of a battery is almost 1000, but supercapacitors have a larger life cycle (10^6)[12]. The specifications of supercapacitor model that will be integrated in the hybrid system has been represented in Table *3* below:

Table 3. Specifications of Supercapacitor Model

Specifications	Value/type
Model name/ manufacturer	Generic type(SC 300F)
Rated Voltage	3V
SOC limits	0%-100%
Rated capacitance	500F
Roundtrip efficiency	95%
Lifetime	30 years

Battery Bank: No matter how many storage systems are used but using a battery is essential in a hybrid energy system because without any battery storage it is hardly possible to store efficiently the power which has been generated and supplied at the time of need. In this hybrid system, a redox-flow or more accurately vanadium flow battery has been used. The redox-flow battery or vanadium flow battery model that has been used in this paper has the following Table 4 properties:

Table 4. Specifications of Vanadium Flow Battery

Specifications	Value/type
Model/Manufacturer Name	Vanadium flow (FB 250-1000)
Nominal Voltage	700V
Nominal Capacity	1.24E+03KWh
Nominal Capacity	1.77E+03Ah
Roundtrip efficiency	70%
Maximum Charge Current	290A
Maximum Discharge Current	441A

The main advantage of using a redox-flow battery is because it can be controlled and monitored. Based on their active species or solvent type, redox flow batteries are classified as aqueous and non-aqueous, respectively. Redox-flow batteries are mostly used in short-term area and frequency regulation, short-term

renewable energy grid integration, long-term transmission and distribution upgrade deferral, and long-term load following etc.[13].

2.3. System Configuration and Control

The system is designed to control and manage the power flow efficiently to the generation sources, storage components, and the load.

Power Management: The power management system monitors continuously how much energy has been produced from the solar PV panels and wind turbines, as well as monitoring the state of charge (SOC) of the supercapacitors and batteries.

Converter: For discharging and charging of the battery bank, a bi-directional converter is used. On the other hand, a separate converter is used for supercapacitors.

The overall system has been designed to control the system efficiently as well as to generate the maximum amount of power. It also optimized for a specific environment as well.

3. METHODOLOGY

This hybrid system is analyzed as well as modeled using software called HOMER, which stands for Hybrid Optimization of Multiple Energy Resources, which is developed by the U.S. National Renewable Energy Laboratory (NREL). To work with HOMER, several data types, including electrical load profiles, renewable resource availability (solar radiation and wind speed), component technical details and costs, and operational constraints, are needed to input.

3.1. Renewable Resource Input and Data Generation

Solar Energy: The solar radiation values are generated for 8760 hours per year using the Graham algorithm in HOMER, which uses realistic hourly data and monthly average solar radiation values based on the latitude. For this study, the location that has been chosen has monthly average solar irradiation about 4.96 KW/m^2/day, based on data from NASA. In below, **Fig. 2** shows various solar radiation for different months which has been taken directly from the HOMER software.

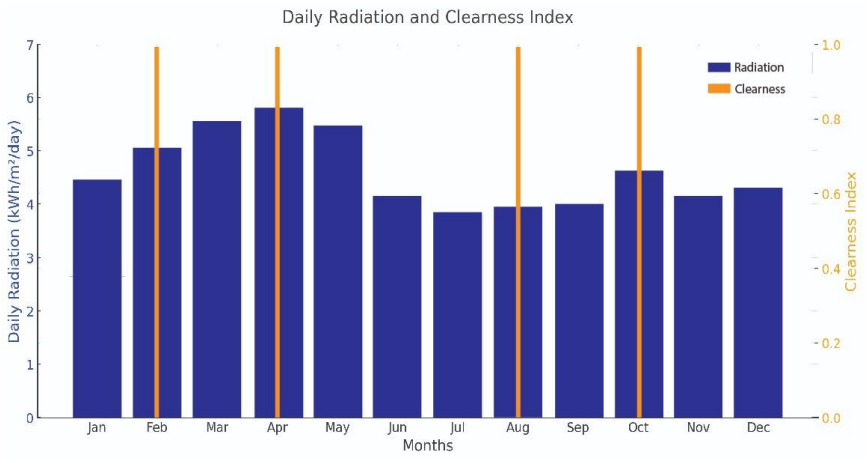


Fig. 2. Monthly average solar irradiation data

Wind Energy: The wind speed input is also based on NASA data as well. Although it is complicated to model, HOMER uses the Weibull distribution, autocorrelation factor, diurnal pattern strength, and hour of peak wind speed to generate synthetic wind speed data. For power generation, wind speed is high enough at Gomatoli, Cox's Bazar which is almost about 5.355 m/s. The monthly average wind

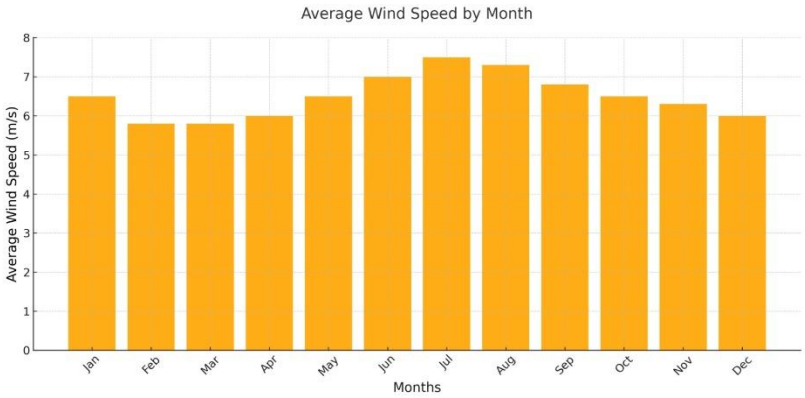


Fig. 3. Monthly average wind speed data

speed has been shown in below **Fig. 3**. Moreover, from **Fig. 4** wind speed varies from almost 0 to 8 in percentage.

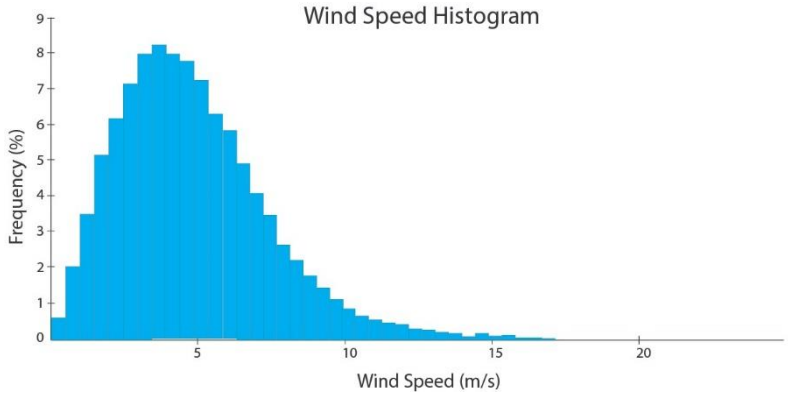


Fig. 4. Frequency vs wind speed

3.2. System Components and Operation Strategy

Power Generation System: The hybrid system at Cox's Bazar includes a solar PV, wind turbines, diesel generators, and battery storage.

Energy Storage System: Energy storage is provided by supercapacitors and redox-flow batteries. Supercapacitors manage the immediate, short-duration power demands due to their high-power density and rapid charge/discharge capabilities. Long-term energy storage is handled by redox-flow batteries because of its scalability and high energy storage capacity.

Operation Strategy: During normal operation, both wind turbines and solar PV supply power. Any excess amount of energy is stored in the supercapacitors and redox-flow batteries.

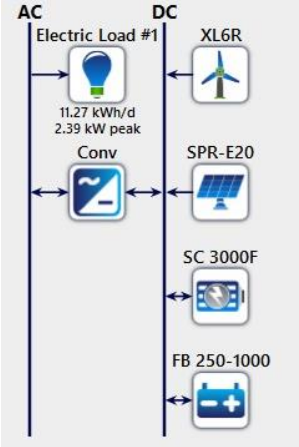


Fig. 5. Load management and AC and DC bus

Load Management and System Optimization

The total system load is modeled to account for daily variations and seasonal changes.

In above **Fig. 5** AC and DC connections has been shown where all the power generation and storage systems are connected to DC bus and the converter is connected to both AC and DC so that it can convert the DC load into AC load to fulfill the energy.

HOMER's economic **analysis** considers the capital costs of the components (solar PV panels, wind turbines, batteries, and diesel generators) and estimates the overall cost of energy production based on various scenarios, such as varying fuel costs or changes in load demand.

4. RESULT & DISCUSSION

In this model, two power generation systems (wind turbine and solar PV) and two energy storing devices (vanadium flow battery and supercapacitor) were incorporated for 357 residential houses. Several combinations of these systems were evaluated to determine the most efficient and cost-effective solution for the energy needs of the community.

The base model, which employed a combination of wind turbine for energy production and vanadium flow battery for storage, was found to have a net present cost (NPC) of $35,630. This configuration generated approximately 1.88 kW/day of energy. With a manageable NPC of $35,630 and an energy production of 1.88 kW/day, this system is well-suited for everyday use in a residential community of this size

To address high demand scenarios, an enhanced hybrid system was tested, integrating solar PV, wind turbine, and supercapacitors for energy storage. This combination proved to be more robust and capable of meeting peak load requirements, generating up to 2.42 kW/day. However, the net present cost for this expanded system was significantly higher at $194,758.

Among the configurations tested, the combination of wind turbines and vanadium flow batteries for the base load, supplemented by solar PV and supercapacitors during peak demand, emerged as the optimal solution. This approach balances cost and energy output, providing both reliability and long-term sustainability for the hybrid energy system.

5. CONCLUSION

This study has demonstrated the successful design of a hybrid energy model tailored to provide sustainable power to 357 homes. The system's foundation is built on a combination of wind turbines and vanadium flow batteries, providing a cost-effective solution with a net present cost of $35,630 and an energy production capacity of 1.88 kW/day. To address peak energy demands, solar PV panels, additional wind turbines, and supercapacitors were integrated, increasing energy output to 2.42 kW/day. This model offers a flexible and efficient approach to managing both regular and peak load demands, making it highly suitable for long-term energy solutions.

Supercapacitors were incorporated to complement the performance of battery, particularly during periods of dynamic instabilities. Supercapacitors are widely utilized across various energy sector applications due to their high energy density and versatility in size. However, when used independently in energy systems, supercapacitors are inefficient because of their low energy density despite having high power density.

The development of this hybrid system addresses the growing need for reliable, renewable energy sources in regions where conventional energy supply may be unreliable or insufficient, especially for the region of Gomatoli in Cox's Bazar, which is rich in both solar and wind energy resources. The utilization of wind and solar energy, along with advanced storage technologies like vanadium flow batteries, provides a highly efficient, environmentally friendly energy solution. Vanadium flow batteries, in particular, offer the advantage of being easily controllable, allowing for energy storage to be adjusted based on demand, which makes the system adaptable and easy to manage.

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