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Viability of a Photovoltaic-Fuel Cell Hybrid Energy System for Sustainable Power Generation in Mymensingh, Bangladesh

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Abstract: We optimize a hybrid energy system configurations by analyzing various factors and project-specific parameters to minimize the cost of energy while meeting electricity demand. One case study shows that a combination of PV panels, a diesel generator, and a battery system achieved the lowest cost of energy at $.484 per unit with an 87% renewable fraction. Another configuration with multiple renewable sources yields a low cost of energy at $.510 per unit and an 87% renewable fraction. The sensitivity analysis is focused on examining the impact of changes in diesel prices, interest rates, and maximum annual capacity shortage on the levelized cost of energy (COE) for hybrid systems. Results show that as diesel prices increase, there is a corresponding rise in COE, highlighting the importance of considering fuel price fluctuations during project planning. An increase in interest rates also leads to higher COE due to increased borrowing costs for companies and investor expectations for higher returns. Additionally, an increase in maximum annual capacity shortage would require additional resources at higher costs to meet growing energy demands while keeping PV production constant. By understanding these impacts, stakeholders can make well-informed decisions regarding the feasibility and sustainability of renewable energy systems.

Keywords: PV system; Hydropower; Techno-economic feasibility; HOMER

1. Introduction

The importance of energy source by Quranic verse: "And there is no creature on earth but that upon Allah is its provision, and He knows its place of dwelling and place of storage. All is in a clear register." (Quran 11:6) This verse emphasizes Allah's knowledge control over all aspects of creation, including energy resources. Renewable energy systems, such as solar, wind, and hydro power technologies, have become attractive options for addressing Bangladesh's severe power crisis. This is primarily due to their minimal environmental impact compared to traditional fossil fuel-based energy generation. Solar power harnesses the energy of the sun through photovoltaic panels or thermal systems. Wind power utilizes the kinetic energy of moving air to generate electricity through wind turbines. Hydroelectric power uses flowing water to turn turbines and produce electricity. These renewable sources provide clean and sustainable alternatives to fossil fuel-based energy generation. In Bangladesh, where dependence on fossil fuels has led to environmental pollution [1] and a significant strain on resources, transitioning towards renewable energy systems can offer multiple benefits. By implementing these technologies, Bangladesh can reduce its reliance on imported fuels and decrease its carbon footprint while also addressing its current severe power crisis. Furthermore, investing in renewable energy infrastructure would create economic opportunities by promoting local manufacturing and installation of renewable technologies in the country [2][3]. Lead-acid batteries are commonly used for short-term energy storage because they are relatively inexpensive and have high power density. However, they have limitations that make them inadequate for long-term energy storage needs. One limitation is their limited cycle life, meaning they can only be charged and discharged for a certain number of times before their performance degrades. This is due to the degradation of the battery's active materials and the formation of sulfation on the lead plates [4]. Over time, this leads to decreased capacity and efficiency, making lead-acid batteries less reliable for long-term energy storage applications. In contrast, electrolyzers play a crucial role in converting surplus electrical energy into hydrogen. Electrolysis is a process in which an electric current passes through water or other electrolytes causing the separation of hydrogen gas from oxygen gas. The generated hydrogen can be stored and used as a clean fuel for various applications such as fuel cells or combustion engines [5][6]. Solar tracking control mechanisms are used to optimize photovoltaic system output by adjusting the orientation or angle of solar panels to maximize sunlight exposure [7]. Despite these optimization techniques, solar and wind energy sources are intermittent due to climate variability. This means that their availability fluctuates depending on weather conditions such as cloud cover or wind strength. To ensure continuous power supply even during periods of low renewable energy generation, backup systems are required. Traditionally, fossil fuel-based generators have been used as backup power sources [8-11]. These generators provide reliable electricity but contribute to greenhouse gas emissions and rely on finite fossil fuel resources. Hybrid systems combining photovoltaic, wind, and hydropower technologies offer an alternative solution by improving overall electricity production efficiency while reducing dependency on fossil fuels. These systems utilize multiple renewable energy sources together with complementary characteristics - solar during daylight hours when there is ample sunlight; wind during periods when there is sufficient wind; hydropower when there is water flow- resulting in more consistent electricity generation throughout different weather conditions. Hydrogen production through electrolyzers in hybrid systems has gained attention because it offers a potential solution for reducing fossil fuel dependency and promoting renewable energy generation [12-14]. Excess electricity generated from renewables can be used to produce hydrogen through electrolysis during peak production times. The produced hydrogen can then be stored for later use when renewable generation drops below demand levels. By integrating these different technologies into hybrid systems with efficient storage options like hydrogen produced from electrolysis, it becomes possible to address the intermittent nature of renewable energies while reducing reliance on traditional fossil fuel-based generators. This promotes sustainable environmental development by increasing clean energy utilization and decreasing carbon emissions associated with power generation.

Several researchers have extensively studied various methodologies [15], focusing particularly on decision-making processes [17], simulation techniques [18], and other related methods [19]. Lau et al. [20] proposed utilizing conventional means such as diesel generators to meet rural electricity demand in their simulation-based approach. Shrestha et al. [21] highlighted the significant impact of rising fossil fuel prices on rural communities and the environment, emphasizing the emissions associated with conventional energy generation. Al-Falahi et al. [22] demonstrated that non-polluting PV and wind energy sources are competitive alternatives to conventional energy sources. Laoun et al. [23] explored solar PV systems for hydrogen production, analyzing the individual component impacts within the process. Yilmaz et al. [24] discussed various methods of hydrogen production using solar energy, including photo-biological generation and photo-electrolysis. Mojtaba et al. [25] conducted a techno-economic feasibility study of a hybrid power system combining photovoltaic and wind energy in Hendijan, Iran. Chavez-Ramirez et al. [26] investigated a hybrid PV-wind-fuel cell system for electricity and hydrogen production at the University of Zacatecas, Mexico. Joshi et al. [27] evaluated different photovoltaic-based hydrogen production systems, with solar thermal concentrating collectors showing higher efficiency than photovoltaic systems. Yang et al. [28] presented a hybrid system incorporating PV-driven alkaline water electrolyzers for efficient hydrogen production in thermal-electricity generation applications.

The research paper by N.A. Noman [29] proposed a hybrid electricity power plant for Delduar, Tangail district in Bangladesh, with a cost of energy (COE) of $.281 per kWh. However, there is no such hybrid generation system in Mymensingh, Bangladesh. Therefore, the proposal for a hybrid electricity system in Mymensingh represents a pioneering effort. The need for a hybrid electricity system arises from the increasing demand for sustainable and reliable power supply in rural areas of Bangladesh. This is particularly important because traditional grid-based systems may not be feasible or economically viable to extend to these remote locations due to infrastructure limitations and cost constraints. A hybrid electricity production system typically combines different renewable energy sources such as solar, wind, biomass, or hydroelectric power with conventional sources like diesel generators to ensure continuous and stable electrical supply. This approach helps address the intermittency and variability of renewable energy sources while reducing dependency on fossil fuels.In the case of Mymensingh, proposing a hybrid electricity system could provide an opportunity to harness local renewable resources effectively and reduce reliance on imported fossil fuels. Additionally, it could contribute to meeting the growing energy demands while mitigating environmental impacts associated with conventional power generation. The introduction of a hybrid electricity production system into Mymensingh could serve as an innovative solution that aligns with national goals for sustainable development and energy security in Bangladesh. It may also offer valuable insights into the feasibility and performance of similar systems in other regions facing similar challenges related to electrification. Overall, proposing a hybrid electricity system for Mymensingh represents an important step towards addressing energy access issues while promoting sustainability and resilience in local power infrastructure.

The main aim of the study is to develop a sustainable and cost-effective hybrid power generation system that incorporates renewable energy sources like PV, wind turbine, and hydropower, alongside conventional sources such as battery and diesel generators. The addition of an electrolyzer and hydrogen tank enables the production of hydrogen as an alternative energy storage solution.For optimization purposes, Homer software is employed to design a system that not only minimizes the cost of energy (COE) and net present cost (NPC), but also increases the renewable energy fraction (RF) while reducing harmful gas emissions. This approach ensures that the system maximizes electricity production from renewable sources while minimizing environmental impact.

The focus on optimizing this hybrid system for Mymensingh Sadar in Bangladesh is particularly significant due to its status as one of the most remote areas in the country. By tailoring a sustainable hybrid power generation system for this area, it addresses critical challenges related to electrification and access to reliable power supply in remote regions.Furthermore, by demonstrating how this optimized hybrid system design can be applied to other remote areas within Bangladesh facing similar challenges, this study provides valuable insights for addressing energy access issues across multiple regions. It showcases the potential replicability of such systems in off-grid or underserved communities seeking reliable electricity supply from a mix of renewable sources combined with conventional technologies.In summary, the proposed hybrid power generation system not only fulfills immediate needs specific to Mymensingh Sadar but also offers broader applicability throughout remote areas in Bangladesh where sustainable electrification solutions are urgently required.

The remaining paper is represented as follows: Section 2 presentsmethodologyof thestudy area; Section 3 introduces the results and discussion for suggested hybrid power plant; Section 4 explains Sensitivity analysis;and the last one is for the conclusions.

2. Methodology

2.1 Geographic characteristics

The study area named Sadar is located in Mymensinghdistrict in Bangladesh on the bank of the old Bhrahmaputra river at 24°75/N latitude and 90°407/E longitude.

2.2 Material and methods for HOMER

This section serves as a crucial reference for researchers who want to understand how a study was conducted and potentially built upon or validate its findings.

2.2.1 HOMER/ Simulation Configuration

The HOMER software framework incorporates simulation, optimization, and sensitivity analysis to accurately assess energy balance across different seasons. By simulating energy configurations, HOMER dynamically models energy production and consumption, ultimately determining feasible solutions over the system's lifetime. Additionally, the framework calculates levelized cost of energy (LCOE) as a key metric for evaluating energy system economics. Following the relation for calculation of NPC is

$$NPC = I + \sum_{i=1}^{n} (C_y)[\frac{1}{(1+d)^i}]$$

Where I is the initial investment, n is the life span of project, C_y is yearly cost (including O: Operation& M: Maintenance and R: replacement), d is for discount rate. The levelized cost of the energy is expressed as-

$$COE = \frac{NPC}{\sum_{i=1}^{n} (E_y)[\frac{1}{(1+d)^i}]}$$

Where, E_y is the yearly served electricity.

2.2.2 Configuration of the proposed system

This section serves as a crucial reference for researchers who want to understand how a study was conducted and potentially built upon or validated its findings. The HOMER software is the electricity energy modeling program for HRES. Homer software is the capable tool for designing, simulating that analyzes hybrid power systems. The program flowchart of the Homer software for Mymensingh, Bangladesh is displayed in Fig. 1.The detailed specifications of them are depicted here.

2.2.3 PV array

The PV array forms a critical component of the energy system, constituting the interconnection of individual PV modules. The HOMER software evaluates power of PV array by using the following equation-

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S}$$

Where, f_{PV} is PV derating factor, Y_{PV} represents the rated capacity of the PV array (KW), I_T introduces global solar radiation (beam plus diffuse) incident on the surface of PV array (kW/m^2), and I_S is the standard radiation rate (kW/m^2). A wide range of photovoltaic (PV) panel sizes spanning from 0 to 4500 kW, were evaluated for optimization across all locations. Ultimately, a 0.75 kW PV panel with a capital cost of $85, was incorporated into the energy scheme in Fig.2. This selection reflects a careful consideration of both capacity requirements and cost-effectiveness in designing the energy system.

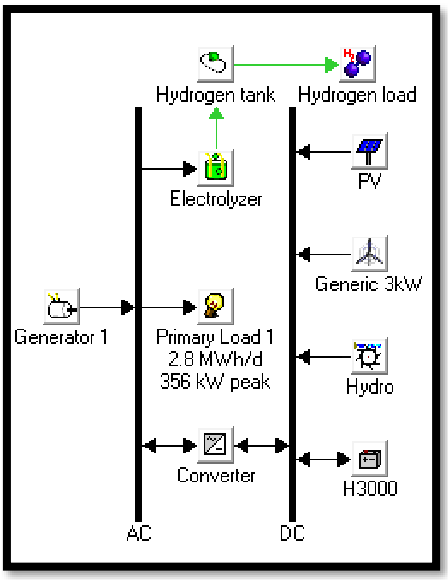

Fig. 1: HOMER software simulation setup(proposed)for Mymensingh sadar, Bangladesh

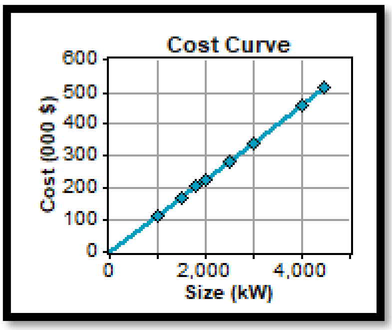

Fig. 2: PV array size vs capital cost

2.2.4 Diesel Generator

To enhance reliability, a 24 kW diesel generator with a capital cost of $10,058 has been integrated into the energy scheme, providing backup power when renewable sources are insufficient [27]. The generator has an annual fuel consumption of 5000 liters and an operational lifetime of 15,000 hours. Optimization considers various sizes of diesel generators ranging from 0 to 300 kW to ensure uninterrupted power supply.

2.2.5 Converter

The converter comprising a rectifier and inverter, plays a crucial role in the energy system by dynamically adapting to PV system operation. It efficiently converts AC to DC during active PV power generation and vice versa for or off-usage. Priced at $651 for a 2 kW unit with 90% efficiency over 15 years[28], its versatility spans from 0 to 400 kW, ensuring optimal energy conversion and system performance. This component optimizes energy utilization and compatibility, emphasizing its importance in the overall scheme.

2.2.6 Estimation of electrical Loads

The overall load system must meet is referred to as the electric loadin Fig.3. The average primary load of study area inMymensingh, Bangladesh is 2832 kWh/day, 356 kW peak, and a load factor of 0.332.

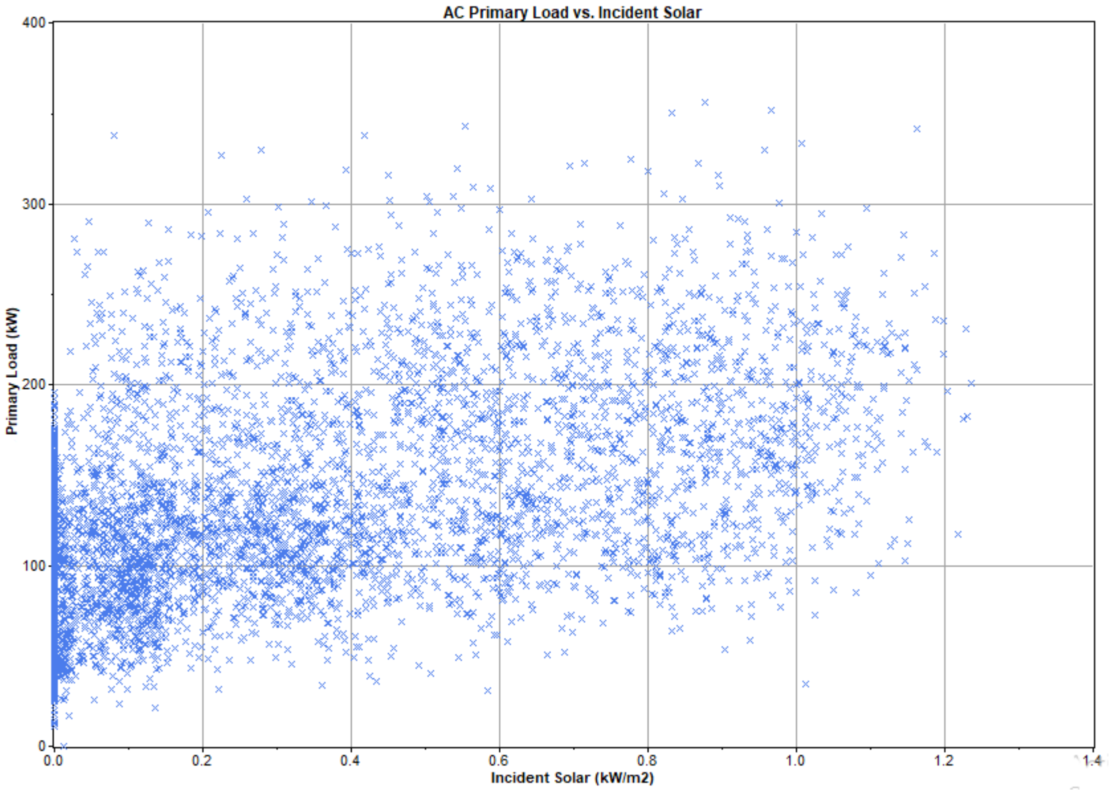

Fig. 3: load profile vs solar radiation

2.2.7Resource assessment

The HOMER model is pivotal in this study, facilitating the exploration of diverse energy resource combinations, including solar, wind, and hydro, to identify the most suitable system configuration. Through systematic resource assessment, HOMER evaluates factors ensuring an economically viable and sustainable energy mix that meets demand.

2.2.7.1 Analysis of the solar energy

The coordinates of area (longitude and latitude) are imported toHOMER program to verify feasibility study of solar energy potentiality in the Mymensingh Sadar, Bangladesh area for proposed hybrid power system. The monthly solar radiation data have been taken from National Aeronautics and Space Administration (NASA) database from the year1983 to 2012[29,30]. Fig.4 indicatesthe daily radiation with a clearness index that is low for July and August. The daily annual calculated solar radiation is4.64 kWh/m^2/day.

2.2.7.2 Analysis of wind energy

The potential of the study area for wind energy is achieved in form of generated electricity. The wind turbine outputs by using HOMER software present the technical-economic feasibility of hybrid system. Fig. 5 shows average monthly wind speed data for research area in the different months. The data for the wind resources have been used for the year fromof 1983 to 2012[30,31]. Accordingto wind resources, few advanced parameters

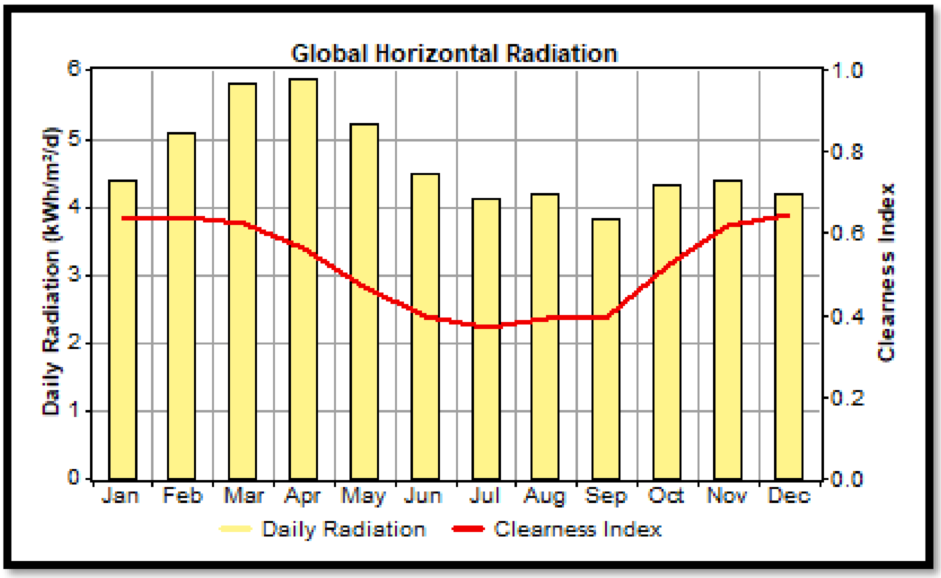

Fig. 4: The solar daily radiation and the clearness index of the research area

are presumed; Weibull value (k) is set around 2, that measures wind speed distribution, autocorrelation factor that quantifies randomness of wind is set to be 0.85, the diurnal pattern strength is set to be 0.25 that implies how the wind speed differs in time during a day, and the hour of peak wind speed is set to be 15. A single unit with a capital cost of $3000 along with equivalent replacement costs, was evaluated for deployment. With a lifespan of 15 years, options for hub heights at both 25 m and 30 m were examined. The scaled annual average, measured at 2.73 m/s, was taken into account for assessing the performance and feasibility of the unit.

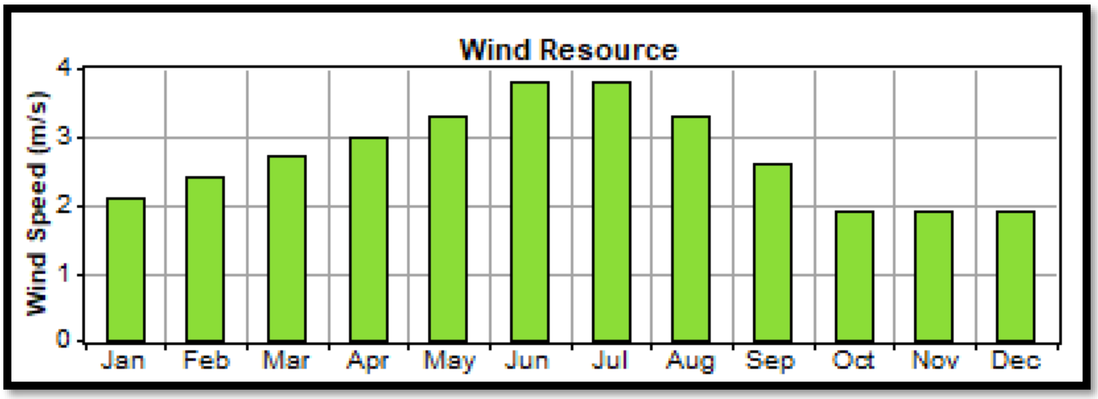

Fig. 5: Wind speed data of different months

2.2.7.3Analysis of hydro power potential

The hydropower generation utilizes energy of falling water to generate electricity. The representation of this hybrid project is proposed according tothe study area location Mymensingh Sadar, near the bank of the Old Bhrahmaputra river.There is a requirement to build a dam in the Old Bhrahmaputra river to regulate turbines properly of the hydro. The water discharge data for the Old Bhrahmaputra river are obtained from Bangladesh Water Development Board (BWDB), Mymensingh[32]. The average water discharge data ratehave been taken from 2000 to 2020. The stream flow data is measured by Acoustic Doppler Current Profiler (ADCP) meter and the hydro acoustic current meter. The scaledannual average discharge of stream flow is 29579 L/s.

2.3 Economic and constraints

The study assumes a project lifetime of 25 years, demonstrating a commitment to long-term sustainability and economic viability. A conservative annual interest rate of 13% to 15% is applied to the financial analysis, considering the time value of money and investment factors. Notably, the system allows for flexibility by not imposing maximum annual capacity shortages, although a 5% to 10% shortage is considered acceptable in the context of renewable energy.

2.4 Storage battery

Given the variability and intermittent nature of renewable energy sources, the integration of batteries is essential to ensure a stable supply of electricity. In this research, the Hoppecke oPzS battery model [33] was chosen for energy storage purposes. This battery type features a nominal voltage of 2V with a capacity of 6kWh and the capital cost for each battery unit is $28522.

2.5 Electrolyzer

The electrolyzer is crucial for converting electricity into hydrogen via electrolysis, splitting water molecules into hydrogen and oxygen gases. Through HOMER software, a search range of 0 to 500 kW optimizes electrolyzer sizes to meet specific energy system needs efficiently. With parameters like a 15-year operational lifetime and 85% efficiency, the tailored electrolyzer design maximizes hydrogen production for sustainable energy applications like fuel cells and energy storage, bolstering overall energy scheme resilience and sustainability.

2.6 Hydrogen Tank

Hydrogen tanks are crucial for storing hydrogen produced within the energy system, with a capacity range from 0 to 500 kg optimized to accommodate diverse production levels. Each tank has a durable 25-year lifespan, ensuring reliable long-term storage capability. With a capital cost of $16 per kg and minimal operational expenses, these tanks are economically attractive and integral to efficient energy storage solutions, supporting sustainability and system resilience.Hydrogen load is shown in Fig.6.

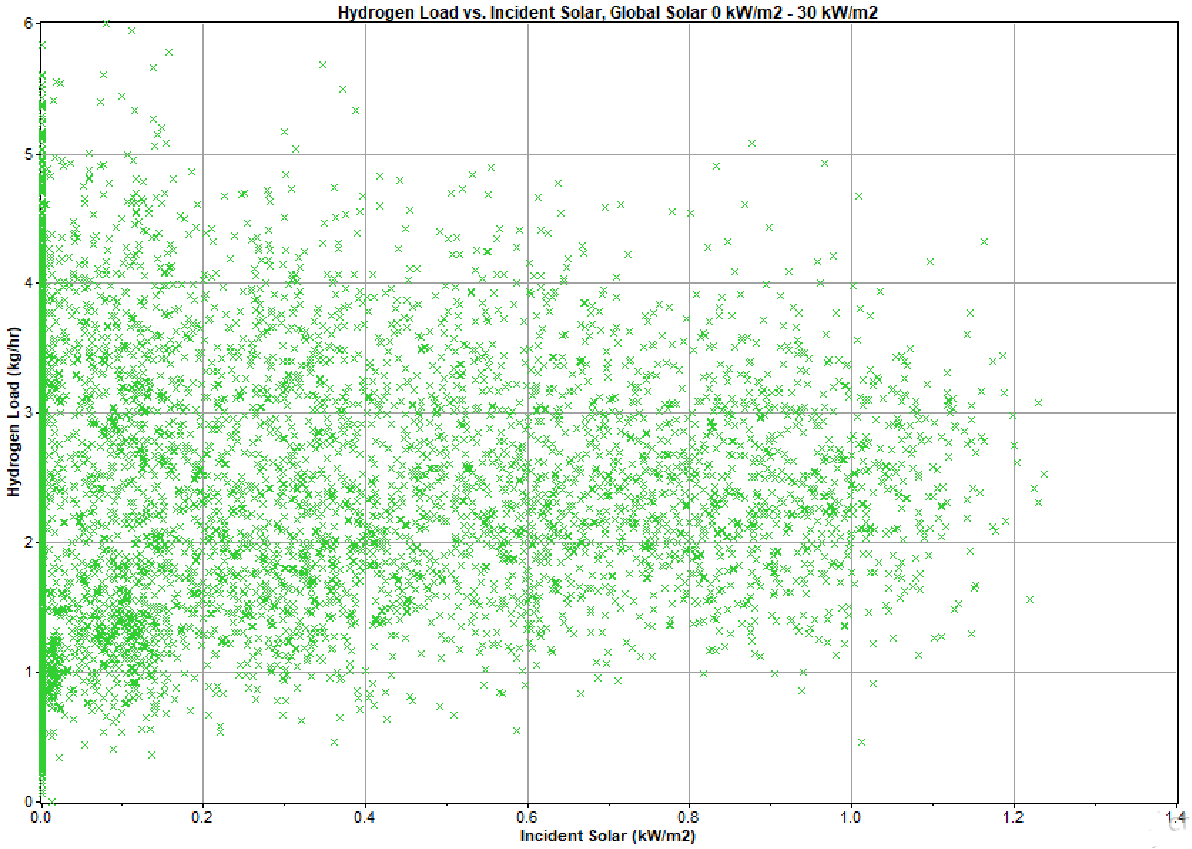

Fig.6: Hydrogen load

3. Results and discussion for suggested hybrid power plant

To assess the performance of different systems and determine the optimal configuration, comprehensive input data is fed into the HOMER software. This software is known for its robust interface and precise analytical capabilities, allowing for simulations over the project lifetime. The goal of the optimization process is to minimize the cost of energy. The HOMER software considers various factors such as renewable energy sources (e.g., PV panels), non-renewable sources (e.g., diesel generators), and energy storage systems (e.g., batteries) to find an optimal combination that meets the energy requirements at a minimal cost. During simulation, the HOMER software takes into account of factors such as solar irradiation, weather patterns, load profiles, electricity prices, fuel costs, system efficiencies, and other relevant parameters specific to the project location. It runs simulations using these inputs to analyze how different system configurations perform over time. By simulating various hybrid configurations and analyzing their performance based on key metrics like cost of energy and renewable fraction (the proportion of energy generated from renewable sources), HOMER identifies an optimized configuration that achieves a balance between cost-effectiveness and reliance on the renewable resources. In this specific case mentioned in Fig. 7, after running multiple simulations with different hybrid configurations comprising PV panels, a diesel generator and a battery system over the project's lifetime horizon, HOMER determined that this particular combination achieved the lowest cost of energy at $0.484 per unit. Additionally, it achieved an 87% renewable fraction indicating that 87% of total electricity consumption was met by renewable sources in this optimized configuration. The optimization process in HOMER involves considering multiple variables simultaneously while finding solutions that satisfy both technical constraints, such as meeting electricity demand, and economic objectives such as minimizing costs. By utilizing advanced algorithms within the software's analytical capabilities, HOMER can identify optimal scenarios based on specific criteria set by users or default settings within its algorithmic framework. This allows users to explore different configurations and analyze trade-offs between renewable energy sources, non-renewable sources, and energy storage systems to achieve the most cost-effective and sustainable solution for their specific project requirements.

The alternative hybrid configuration mentioned consists of multiple renewable energy sources, including photovoltaic (PV) solar panels, wind turbines, batteries for energy storage, hydropower systems, a diesel generator for backup power, and a converter to manage the integration of these different technologies. This combination allows for a more diverse and flexible energy system that can optimize the use of resources and improve overall efficiency. One key advantage of this hybrid configuration is its ability to yield a relatively low cost of energy (COE) at $0.510. The integration of multiple renewable sources helps to reduce reliance on expensive fossil fuels and decrease operational costs in the long run. This makes renewable energy more economically feasible and competitive with conventional power generation methods. Furthermore, this hybrid configuration boasts an 87% renewable fraction. This means that the majority (87%) of the electricity generated comes from clean and sustainable sources such as PV solar panels, wind turbines, and hydropower systems. By relying less on non-renewable resources like fossil fuels or grid electricity from conventional power plants, carbon dioxide emissions are significantly reduced. The development of hybrid power plants utilizing this alternative configuration presents significant opportunities for advancing renewable technology in several ways:1. Technological Integration: Hybrid power plants require advanced control systems to efficiently manage various components such as PV panels, wind turbines, batteries, converters, etc. Developing sophisticated control algorithms that optimize resource allocation based on real-time data analysis enables better integration between different technologies.2. Energy Storage Advancements: The inclusion of battery storage in the hybrid configuration allows for better management of intermittent energy sources like solar and wind by storing excess electricity during peak production periods or low demand times to be used when needed later.3. Grid Independence: Hybrid power plants can contribute to increased grid independence by reducing dependence on centralized conventional power grids or imported fossil fuels. By generating electricity locally using a mix of renewables tailored to available resources in the research area (such as sunlight or wind), communities can have more control over their energy supply while reducing vulnerability to price fluctuations or supply disruptions.4. Environmental Impact Mitigation: By increasing reliance on clean energy sources through high renewable fractions in hybrid configurations, the environmental impact of electricity generation can be significantly mitigated. Reduced carbon dioxide emissions contribute positively towards climate change mitigation efforts and help to protect local environments from pollution associated with traditional fossil fuel-based generation methods.

PV (kW)	G3	Hydro (kW)	Label (kW)	H3000	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	COH ($/kg)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
2800			400		400	220	250	$ 839,167	378,095	$ 3,437,788	0.484	26.900	0.87	0.00	315,079	5,033
2800		92.0	400		400	220	250	$ 842,048	378,095	$ 3,440,669	0.484	26.922	0.87	0.00	315,079	5,033
2800			400	1	400	220	250	$ 867,689	379,680	$ 3,477,202	0.489	27.209	0.87	0.00	316,400	5,058
2800		92.0	400	1	400	220	250	$ 870,570	379,680	$ 3,480,083	0.490	27.231	0.87	0.00	316,400	5,058
2800	50		400		400	220	200	$ 988,367	377,454	$ 3,582,578	0.504	28.101	0.87	0.00	314,545	5,027
2800	50	92.0	400		400	220	200	$ 991,248	377,454	$ 3,585,459	0.505	28.123	0.87	0.00	314,545	5,027
2800	50		400	1	400	220	200	$ 1,016,889	378,748	$ 3,619,994	0.510	28.395	0.87	0.00	315,623	5,048
2800	50	92.0	400	1	400	220	200	$ 1,019,770	378,748	$ 3,622,875	0.510	28.417	0.87	0.00	315,623	5,048
			800		1	150	75	$ 486,792	1,305,846	$ 9,461,774	1.332	74.616	0.00	0.00	1,088,205	8,759
		92.0	800		1	150	75	$ 489,673	1,305,846	$ 9,464,654	1.332	74.638	0.00	0.00	1,088,205	8,759
			800	1	1	150	75	$ 515,314	1,305,776	$ 9,489,819	1.336	74.837	0.00	0.00	1,088,147	8,759
		92.0	800	1	1	150	75	$ 518,195	1,305,776	$ 9,492,700	1.336	74.860	0.00	0.00	1,088,147	8,759
	50		800		1	150	75	$ 636,792	1,305,800	$ 9,611,459	1.353	75.795	0.01	0.00	1,088,166	8,759
	50	92.0	800		1	150	75	$ 639,673	1,305,800	$ 9,614,340	1.353	75.818	0.01	0.00	1,088,166	8,759
	50		800	1	3	150	75	$ 665,965	1,305,653	$ 9,639,623	1.357	76.017	0.01	0.00	1,088,044	8,759
	50	92.0	800	1	3	150	75	$ 668,846	1,305,653	$ 9,642,504	1.357	76.040	0.01	0.00	1,088,044	8,759

Fig. 7:Simulation results from HOMER softwarefor Mymensingh

3.1 PV–wind–Hydro-diesel–electrolyzer power option

The hybrid power system combining PV, wind, hydro, diesel, and an electrolyzer offers a unique and versatile approach to energy generation. This configuration allows for the seamless integration of renewable sources like solar and wind with non-renewable sources like diesel. Additionally, the inclusion of an electrolyzer enables the production of hydrogen fuel from excess electricity.

One key aspect that sets this hybrid system apart is its ability to optimize energy production throughout the year. By analyzing monthly average electrical production, as shown in Fig. 8, valuable insights can be gained regarding the system's performance

and its potential benefits. This provides a visual representation of how energy production varies over different months. The graph shows a clear pattern reflecting seasonal fluctuations in renewable energy sources such as solar and wind. During certain months when sunlight or wind conditions are favorable (e.g., summer or windy seasons), there is higher electricity generation from PV panels and wind turbines. Conversely, during periods when sunlight or wind conditions are less favorable (e.g., winter or calm seasons), there is lower electricity generation from these renewable sources alone. However, by incorporating other components like hydro systems and a diesel generator into the hybrid configuration, consistent electricity supply can be maintained throughout the year. The combination of multiple energy sources allows for better utilization of available resources to ensure reliable power generation even during periods of low renewable energy availability. In times when solar or wind resources are limited due to weather conditions or seasonal variations, other components like hydropower systems can compensate by providing continuous electricity output. The inclusion of a diesel generator further enhances reliability by serving as backup power during extended periods without sufficient renewable energy supply. This ensures uninterrupted power supply even under unfavorable weather conditions or unforeseen circumstances. By examining the monthly average electrical production through this figure, policymakers, researchers, and stakeholders gain valuable insights into how the hybrid power system performs under varying environmental factors. These insights can guide decision-making processes related to optimizing resource allocation, improving overall system efficiency, assessing economic viability, and predicting future adjustments based on changing environmental patterns.
The provided data describes the performance metrics of a photovoltaic (PV) system in Fig.9. It operates with a rated capacity of 2,800 kW, indicating its maximum potential power output. The mean output of 475 kW and daily energy output of 11,394 kWh illustrates the average electricity generation capability of the PV system. With a capacity factor of 17.0%, the system efficiently utilizes sunlight resulting in an estimated operation of 4,373 hours per year and a total annual production of 4,158,909 kWh showcasing its significant contribution to overall energy production.
Fig. 10 highlights the importance of the wind turbine in the hybrid power system configuration. The graph demonstrates the substantial contribution of the wind turbine to overall energy production with a maximum output of 140 kW. This indicates a significant capacity for harnessing wind energy. Furthermore, this showcases the operational duration of the wind turbine which spans 3,638 hours per year. This consistent performance throughout various weather conditions and seasons emphasizes the reliability and dependability of wind energy as a key component in the hybrid system. The high operational duration underscores that wind energy plays a pivotal role in meeting electricity demand and reducing reliance on non-renewable sources like diesel generators. It also reflects successful integration and utilization of

available wind resources within this particular region or setting. This consistency in performance highlights not only the potential for capturing renewable energy through winds but also showcases its ability to contribute significantly in meeting electricity needs during periods when other renewable sources may be less productive. By leveraging consistent winds and optimizing generation from turbines, hybrid systems can effectively balance renewable and non-renewable sources while ensuring reliable power supply throughout different seasons or weather patterns.
Fig.11 presents a comprehensive analysis of the diesel generator (DG) within the hybrid power system. The graph provides valuable information about the DG's cost indices and operational characteristics, shedding light on its importance in ensuring reliable power supply. One key aspect highlighted in Fig. 11 is the operational lifetime of the DG, which spans 5,048 hours per year. This indicates that the DG plays a crucial role in providing backup power during times when renewable sources such as solar or wind energy may be limited or unavailable. By operating for such a significant duration, the DG ensures uninterrupted electricity supply and enhances system resilience. Additionally, this showcases the maximum electrical output of the DG, which stands at 324 kW. This high output capacity further contributes to system reliability by providing ample power to meet electricity demand even during peak usage periods. The combination of an extensive operational lifetime and substantial electrical output emphasizes how the DG serves as a reliable backup option within this hybrid system configuration. It acts as a contingency measure when renewable sources are unable to meet electricity needs due to factors like weather conditions or fluctuations in availability. The presence of a robust DG in this hybrid system not only supports continuous power supply but also helps to maintain stable voltage levels and grid stability during periods when renewable energy generation may be intermittent or insufficient. The PV-wind-hydro-diesel-electrolyzer hybrid power system stands as a remarkable energy solution, seamlessly blending renewable and non-renewable options.

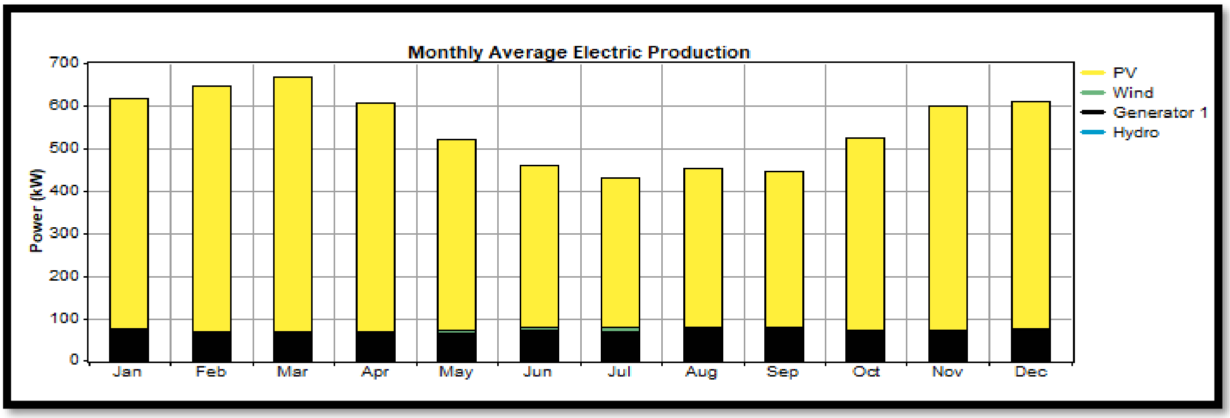

Fig.8: Monthly average electrical production

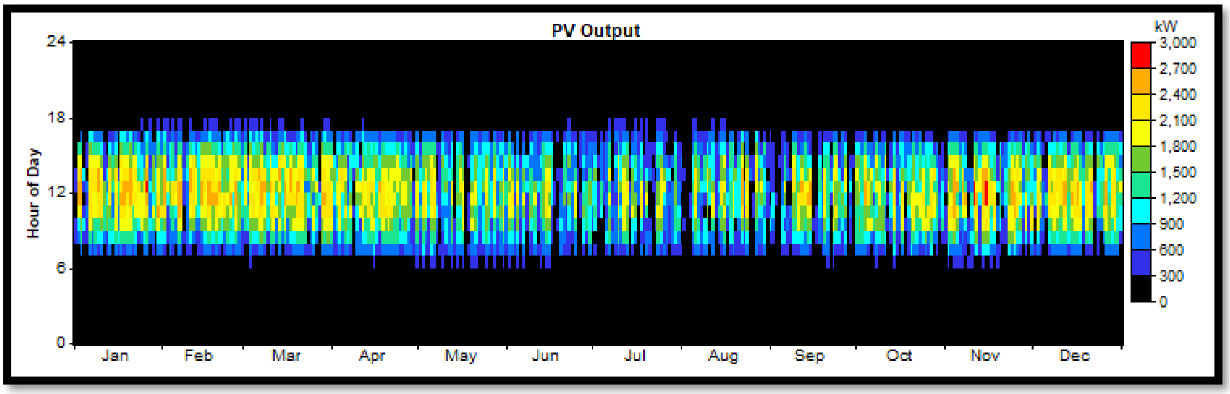

Fig.9: Monthly PV output

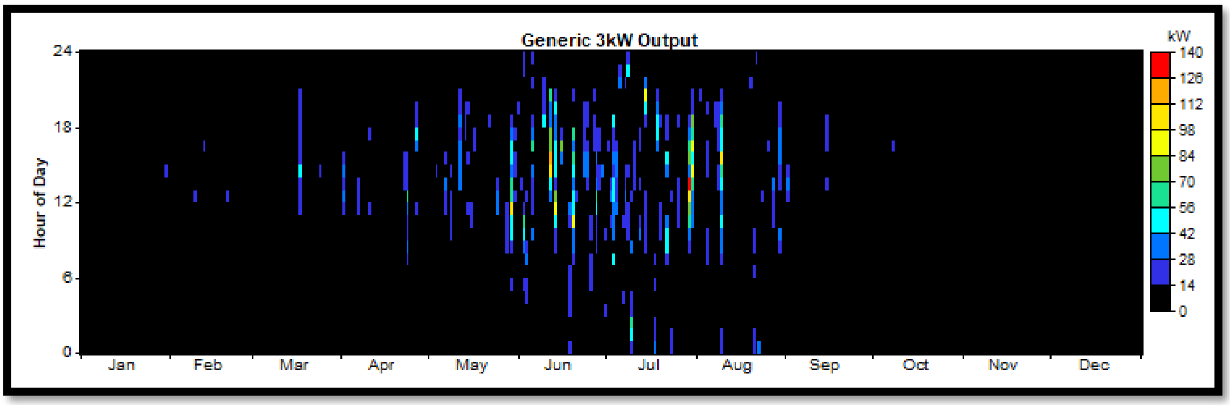

Fig.10: Monthly wind turbine output

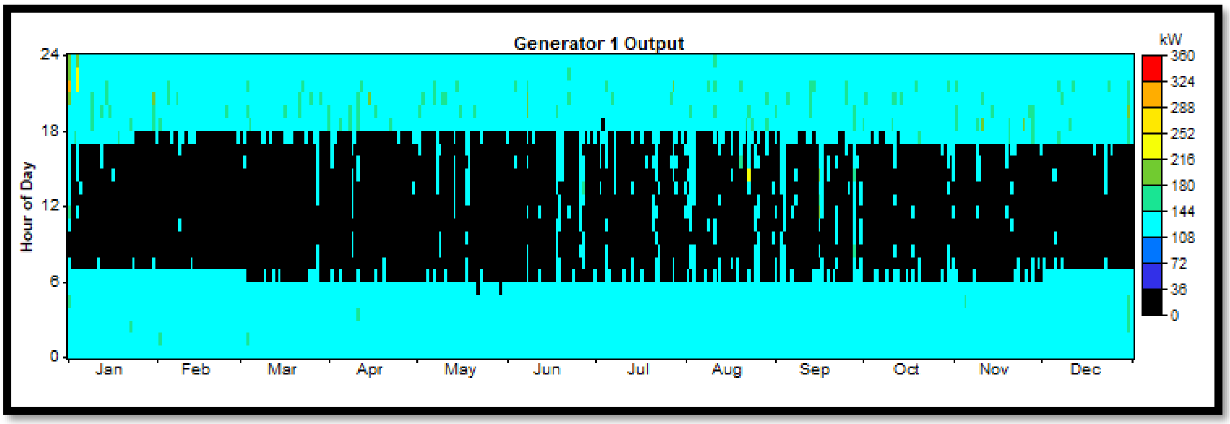

Fig.11: DG generator output

3.2. Emission

Table1 provides information on the annual emissions of various pollutants from a diesel generator. The largest contributor to these emissions is carbon dioxide (CO2), with an estimated release of 831,140 kilograms per year (kg/yr). Carbon monoxide (CO) emissions are relatively low at 2,052 kg/yr, but it is important to note that CO is a toxic gas. Unburned hydrocarbons, particulate matter, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) are also emitted by the generator in smaller quantities: 227, 155, 1669, and 18306 kg/yr respectively. These pollutants can have negative impacts on air quality and human health if not properly controlled or mitigated.

Table 1: Pollution emission

Pollutants	Emissions (kg/year)
Carbon dioxide	831,140
Carbon monoxide	2,052
Unburned hydrocarbons	227
Particular matter	155
Sulfur dioxide	1,669
Nitrogen oxides	18,306

4. Sensitivity analysis

In the sensitivity analysis conducted using HOMER software, the key parameter being examined the diesel price. The analysis aims to understand how changes in diesel prices affect the levelized cost of energy (COE) for the energy system option. The analysis considers an interest rate of 14% and a maximum annual capacity shortage of 30%. The COE for the hybrid option is against diesel price values ranging from $1.2 to $1.4.

The results depicted in Fig.12 show that as diesel prices increase, there is a subsequent rise in the levelized cost of energy for the hybrid option. This indicates that changes in diesel prices have a significant impact on the economic viability of the hybrid system. Diesel fuel is often used as a backup or supplementary power source in hybrid systems, especially in areas where renewable energy sources like solar PV are insufficient to meet demand consistently. Diesel prices can fluctuate due to the factors such as global oil market dynamics and events.When diesel prices increase, it directly affects operating costs associated with running generators or backup systems that rely on this fuel source. These higher costs are then reflected in an increase in the levelized cost of energy for the hybrid system. Conversely, when diesel prices decrease, it reduces operating costs subsequently lowering the levelized cost of energy for the hybrid system.This sensitivity analysis highlights why considering fuel prices is crucial during project planning and decision-making processes regarding renewable energy systems with backups or supplementary components like diesel generators. Understanding how changes in key parameters impact economic viability helps stakeholders to make informed decisions regarding project feasibility and long-term sustainability.

The cost of energy (COE), particularly concerning the impact of interest rates in Fig.13, can be understood by considering the financial dynamics.When the interest rate increases, the cost of borrowing money also increases. This has a direct impact on the cost of equity (COE), which is a measure of the return required by investors to compensate for the risk associated with an investment. A higher interest rate means that investors will demand a higher return on their investment to offset the increased cost of borrowing. As a result, companies seeking investments will have to offer higher returns or dividends to attract investors, increasing their COE.Additionally, a higher interest rate can increase borrowing costs for companies, making it more expensive for them to finance projects or expansions. This can also contribute to an increase in COE as companies factor in these additional costs when determining their required return on the investment.Overall, an increase in interest rates tends to lead to higher COE as companies face greater costs and investor expectations for returns rise.

When the maximum annual capacity shortage increases, it means that there is a higher demand for energy than can be supplied by the existing capacity. This can happen due to factors such as population growth, increased industrial activity, or changes in consumption patterns.Fig. 14, represents the relationship between the maximum annual capacity shortage and the cost of energy (COE) with constant PV production, where we need to consider how this increase in demand affects the cost of energy.As the maximum annual capacity shortage increases, there is a strain on the existing energy infrastructure to meet the growing demand. To bridge this gap between supply and demand, additional measures may require, such as relying on alternative sources of energy or importing electricity from other regions.These alternative measures often come at a higher cost compared to regular supply sources. For instance, using backup generators or purchasing electricity from other regions may involve higher production costs or transmission fees.Therefore, when there is an increase in maximum annual capacity shortage while keeping PV production constant, additional resources will be needed to meet the increased demand for energy. These resources often come at a higher cost due to their limited availability or higher operational expenses.Consequently, with an increase in maximum annual capacity shortage and constant PV production levels depicted, it is expected that this will lead to an increase in overall costs associated with meeting the growing energy demands through alternative means.

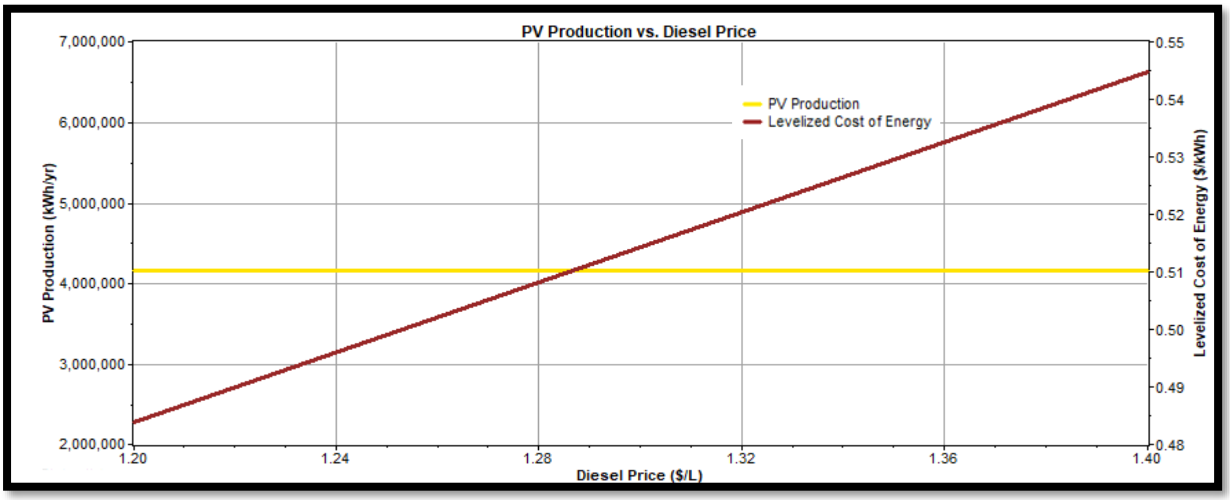

Fig. 12: Sensitivityanalysis for PV production vs diesel price vs levelized cost of energy

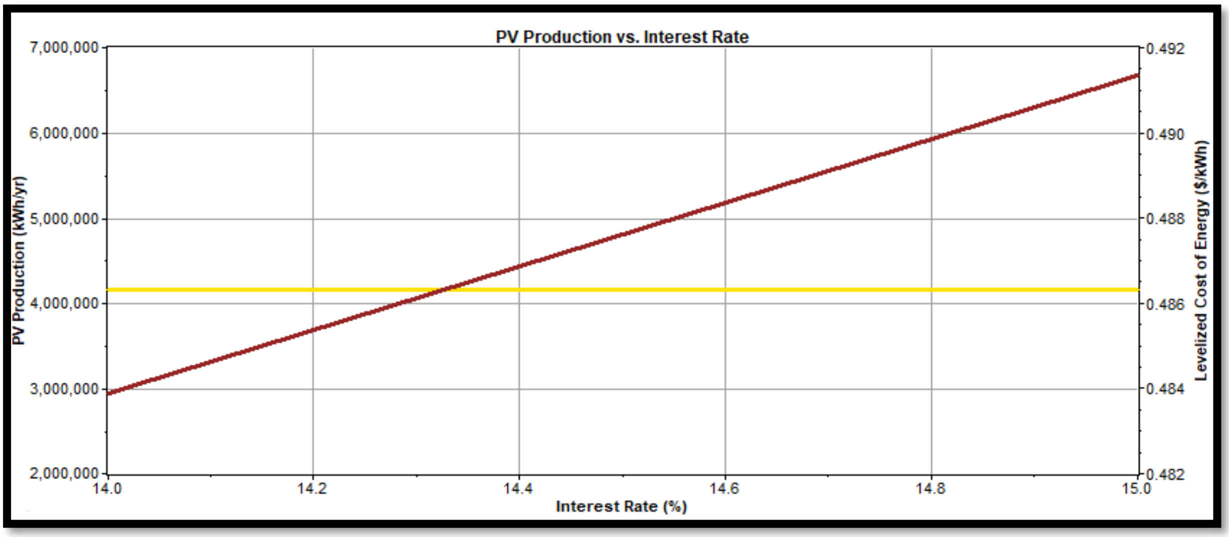

Fig. 13:Sensitivityanalysis for PV production vs interest rate vs levelized cost of energy

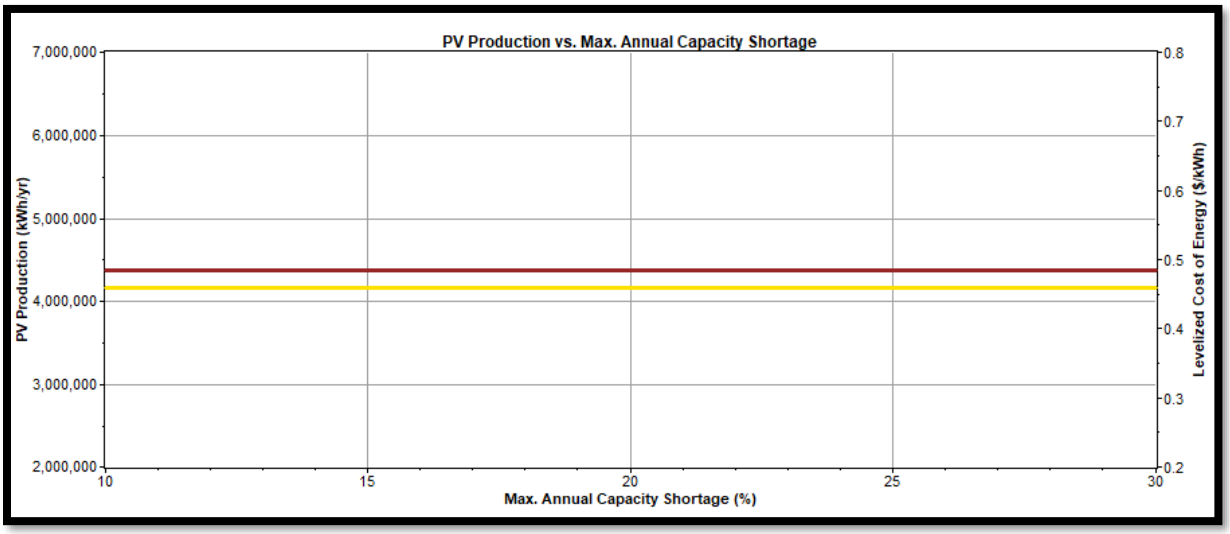

Fig. 14:Sensitivity analysisfor PV production vs max. Annual capacity shortagevs levelized cost of energy

4. Conclusions

The HOMER software is used to optimize hybrid energy system configurations by analyzing various factors such as renewable and non-renewable energy sources, energy storage systems, and project-specific parameters. By running the simulations, the software identifies the optimal combination that minimizes the cost of energy while meeting electricity demand. In one specific case, a hybrid configuration of PV panels, a diesel generator, and a battery system achieved the lowest cost of energy at $.484 per unit and an 87% renewable fraction. An alternative configuration with multiple renewable sources including PV panels, wind turbines, batteries, hydropower systems, and a diesel generator yielded a low cost of energy at $.510 and an 87% renewable fraction. These configurations offer economic feasibility while reducing reliance on fossil fuels and decreasing carbon emissions. Advancements in technology integration for hybrid power plants can lead to better resource allocation and grid independence while mitigating environmental impacts through increased reliance on clean energy sources.

The sensitivity analysis conducted using the HOMER software isfocused on examining the impact of changes in diesel prices, interest rates, and maximum annual capacity shortage on the levelized cost of energy (COE) for hybrid energy system options. These results show that as diesel prices are increased, there is a corresponding rise in the levelized cost of energy for hybrid systems. This underscores the significance of considering fuel price fluctuations during project planning to ensure economic viability and long-term sustainability. Additionally, the analysis reveals that an increase in the interest rates leads to a higher COE due to increased borrowing costs for companies and investor expectations for a higher returns. Furthermore, with an increase in maximum annual capacity shortage while keeping PV production constant, additional resources would be needed to meet growing energy demands at higher costs.Overall, by understanding how key parameters impact economic viability through sensitivity analysis, stakeholders can make informed decisions regarding project feasibility and long-term sustainability when considering renewable energy systems with backup or supplementary components like diesel generators.

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5. References

1. L. B. Braga, J. L. Silveira, M. E. Da Silva, C. E. Tuna, E. B. Machin, and D. T. Pedroso (2013). "Hydrogen production by biogassteam reforming: A technical, economic and ecological analysis," Renewable and Sustainable Energy Reviews, vol. 28, pp.166–173.
2. M. A. Habib, K. M. A. Kabir, and J. Tanimoto (June 2022). "Evolutionary game analysis for sustainable environment under two powergeneration systems," Evergreen Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 09, Issue 02,pp. 323-341.

3. V. Garcia-Heller, R. Espinasa, and S. Paredes (2016). “Forecast study of the supply curve of solar and wind technologies in Argentina,Brazil, Chile and Mexico,” Renew Energy, vol. 93, pp. 168–179.
4. A. A. Solomon, D. M. Kammen, and D. Callaway (2016). “Investigating the impact of wind-solar complementarities on energy storagerequirement and the corresponding supply reliability criteria,” Appl Energy, vol. 168, pp. 130–145.
5. P. G. Mura, R. Baccoli, R. Innamorati, and S. Mariotti (2015). “An energy autonomous house equipped with a solar PV hydrogenconversion system,” Energy Procedia, vol. 78, pp. 1998–2003.
6. S. M. M. Ehteshami, S. Vignesh, R. K. A. Rasheed, and S. H. Chan (2016). “Numerical investigations on ethanol electrolysis forproduction of pure hydrogen from renewable sources,” Appl Energy, vol. 170, pp. 388–393.
7. M. M. U. Rashid, M. A. Habib, and M. M. Hasan (2019). “Design and construction of the solar photovoltaic simulation system withthe implementation of MPPT and boost converter using MATLAB/Simulink,” Asian Journal of Current Research, vol. 3, pp.27–36.
8. Md. Samiul Islam, Faridul Islam, Md. Ahsan Habib (2022). "Feasibility analysis and simulation of the solar photovoltaicrooftop system using PVsyst software", International Journal of Education and Management Engineering(IJEME),Vol.12, No.6, pp.21-32.
9. S. Sinha and S. S. Chandel (2015). “Review of recent trends in optimization techniques for solar photovoltaic-wind based hybridenergy systems,” Renewable and Sustainable Energy Reviews, vol. 50, pp. 755–769.
10. M. A. Habib (2022). “Wind speed data and statistical analysis for Rangpur district in Bangladesh,” Journal of Electrical Engineering,Electronics, Control and Computer Science –JEEECCS, Volume 8, Issue 30, pp. 1-10.
11. T. Maatallah, N. Ghodhbane, and S. Ben Nasrallah (2016). “Assessment viability for hybrid energy system (PV/wind/diesel) withstorage in the northernmost city in Africa, Bizerte, Tunisia,” Renewable and Sustainable Energy Reviews, vol. 59, pp. 1639–1652.
12. Md. S. Islam, N. A. Noman, and Md. A. Habib (Oct. 2022). “The best techno-economic aspects of the feasibility study concerning theproposed PV-wind-hydro hybrid system in Nilphamari, Bangladesh,” International Journal of Education and ManagementEngineering, vol. 12, no. 5, pp. 24–37.
13. Z. Abdin, C. J. Webb, and E. M. A. Gray (Dec. 2015). “Solar hydrogen hybrid energy systems for off-grid electricity supply: A criticalreview,” Renewable and Sustainable Energy Reviews, vol. 52. Elsevier Ltd, pp. 1791–1808.
14. M. N. Uddin and W. M. A. W. Daud (2014). “Technological diversity and economics: Coupling effects on hydrogen production frombiomass,” Energy and Fuels, vol. 28, no. 7, pp. 4300–4320.

15. M. A. Habib (2022). "Game Theory, Electrical power market and dilemmas," Journal of Electrical Engineering, Electronics, Controland Computer Science – JEEECCS, vol. 8, pp. 33–42.
16. M. A. Habib (2022). "The application of asymmetric game in the electrical power market," Journal of Electrical Engineering,Electronics, Control and Computer Science –JEEECCS.
17. M. A. Habib (2019).'Can people detect dilemma strength in a 2 player 2 strategy game?': A Survey Game," Proceeding ofinternational exchange and innovation conference on engineering & sciences (IEICES), vol. 5, pp. 116–117.
18. M. A. Habib, K. M. A. Ariful Kabir, and J. Tanimoto (2020).'Do humans play according to the game theory when facing the social dilemma situation?' A survey study," Evergreen, vol. 7, no. 1, pp. 7–14.
19. M. A. Habib, M. Tanaka, and J. Tanimoto (2020). "How does conformity promote the enhancement of cooperation in the network reciprocity in spatial prisoner's dilemma games?" Chaos Solitons Fractals, vol. 138, p. 109997.
20. K. Y. Lau, M. F. M. Yousof, S. N. M. Arshad, M. Anwari, and A. H. M. Yatim (2010). "Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions," Energy, vol. 35, no. 8, pp. 3245–3255.
21. R. M. Shrestha, G. Anandarajah, and M. H. Liyanage (2009). "Factors affecting CO_2 emission from the power sector of selected countries in Asia and the Pacific," Energy Policy, vol. 37, no. 6, pp. 2375–2384.
22. M. D. A. Al-falahi, S. D. G. Jayasinghe, and H. Enshaei (2017). "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system," Energy Convers Manag, vol. 143, pp. 252–274.
23. B. Laoun, A. Khellaf, M. W. Naceur, and A. M. Kannan, "Modeling of solar photovoltaic-polymer electrolyte membrane electrolyzer direct coupling for hydrogen generation (2016)." Int J Hydrogen Energy, vol. 41, no. 24, pp. 10120–10135.
24. F. Yilmaz, M. T. Balta, and R. Selbaş (2016). "A review of solar based hydrogen production methods," Renewable and Sustainable Energy Reviews, vol. 56, pp. 171–178
25. M. Qolipour, A. Mostafaeipour, and O. M. Tousi (2017). "Techno-economic feasibility of a photovoltaic-wind power plantconstruction for electric and hydrogen production: A case study," Renewable and Sustainable Energy Reviews, vol. 78, pp. 113–123.
26. A. U. Chávez-Ramírez, J. C. Cruz, R. Espinosa-Lumbreras, J. Ledesma-García, S. M. Durón-Torres, and L. G. Arriaga (2013). "Design and set up of a hybrid power system (PV-WT-URFC) for a stand-alone application in Mexico," Int J Hydrogen Energy, vol. 38, no. 28, pp. 12623–12633.

27. A. S. Joshi, I. Dincer, and B. V. Reddy (2011). "Solar hydrogen production: A comparative performance assessment," Int J Hydrogen Energy, vol. 36, no. 17, pp. 11246–11257.
28. Z. Yang, G. Zhang, and B. Lin (2015). "Performance evaluation and optimum analysis of a photovoltaic-driven electrolyzer system for hydrogen production," Int J Hydrogen Energy, vol. 40, no. 8, pp. 3170–3179.
29. Noman, N. A., Islam, M. S., Habib, M. A., and Debnath, S. K. (2023). "The Techno-Economic Feasibility Serves to Optimize the PV-Wind-Hydro Hybrid Power System at Tangail in Bangladesh". International Journal of Education and Management Engineering (IJEME), 13(3), 19-32.