IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 20, 2022, accepted March 31, 2022, date of publication April 4, 2022, date of current version April 12, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3164677

Sustainable Microgrid Analysis for Kutubdia Island of Bangladesh

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ABSTRACT Uninterrupted power supply with sustainable microgrid remains a big challenge for Kutubdia Island in Bangladesh. However, the majority of study has been focused on the techno-economic aspects of producing electricity in support of this isolated area. To bridge the gap, the present study proposes a methodology for assessing off-grid hybrid microgrid pertaining to the priorities of four key sustainability performance indicators (KSPI): economy, environment, technology, and society. The evaluation process also includes total 13 sets of sub-indicators under KSPI, such as levelized cost of energy, return on investment, CO_2 emissions, renewable fraction, excess electricity, unmet load, land usage, job creation etc. The comprehensive value of KSPI regarding economic, environmental, technical, and social priorities are computed using fuzzy logic Mamdani type rules, which facilitates human judgment in linguistic terms and eliminates weightage ambiguity. Seven microgrid scenarios integrating locally accessible resources have been scored and ranked to identify suitable configuration. According to the findings, the PV/Wind/Diesel/Converter/Battery combination reveals best option considering economic priority. On the other hand, the PV/Wind/Converter/Battery alternative receives excellent performance scores and is recommended in both environmental and social categories. However, the PV/Diesel/Converter/Battery arrangement outperforms the others architectures and gets preference for technical reasons. Additionally, the electrical, financial, emission, and sensitivity analysis are carried out for a selected microgrid in Kutubdia. This assessment framework can assist academics, policymakers and investors for planning microgrid in a better way based on sustainable dimensions.

INDEX TERMS Cost of energy, fuzzy logic, Kutubdia, microgrid, multi-criterion decision analysis, net present cost, renewable energy, solar PV, sustainability, wind turbine.

I. INTRODUCTION

Kutubdia is a small island of the southern coast of Bangladesh, surrounded by the Bay of Bengal [1], [2]. Approximately 1,07,221 people live in this isolated location [3]. The total area is 215.8 km^2 and 91 kilometers distance from the main land separated by a sea channel, with 8903.22 hectors of agricultural land [4]. The Figure 1 presents the island's location at 21.82°N latitude and 91.86°E longitude. There are roughly 13,236 cows and buffalos [5]. Only the lighthouse was built during the British rule. It is famous for salt production, and dried fish, locally known as Shutki [6]. The majority of the population currently uses candles, kerosene wick lamps, and lanterns to illuminate their homes. The economically solvent families frequently install solar panels for lighting, fans, televisions, and cellphone charging [7]. A 1MW wind farm was built in 2008, although it was severely damaged by a cyclone and has now been repaired. Currently, the Bangladesh Power Development Board (BPDB) produce electricity by diesel generators for a short duration. Renewable sources are becoming more popular around the world as a means of ensuring energy security and lowering greenhouse gas emissions [8]. The energy policy of Bangladesh encourages and supports both public and private sector investment to promote ecofriendly renewable energy. Natural gas is the most prevalent fuel for power stations, but its reserve is running out. As a result, seeking new sources of energy has become essential. Furthermore, energy subsidies are difficult since the significant increase in fuel and power prices will have a negative impact on the national economy. Bangladesh aims to reduce CO_2 emissions by incorporating renewable resources such as solar

The associate editor coordinating the review of this manuscript and approving it for publication was Youngjin Kim.

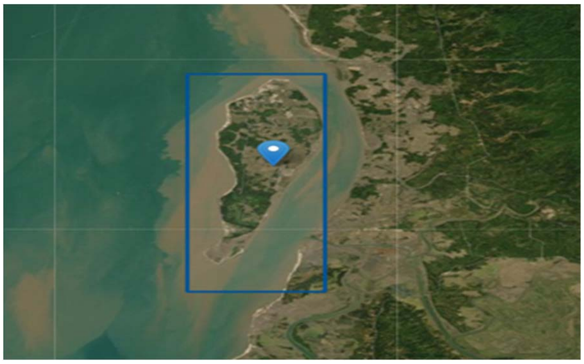


FIGURE 1. Google map of Kutubdia Island, Bangladesh.

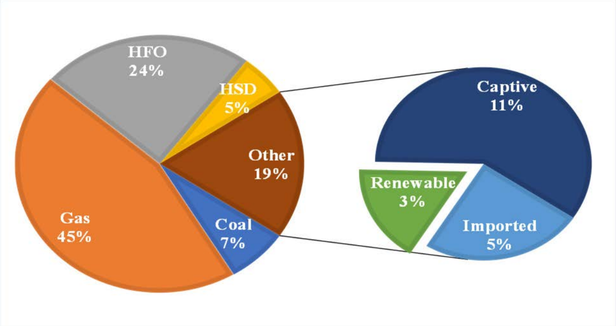


FIGURE 2. Installed energy mix of power system, Bangladesh.

and wind [9]. Currently the total installed plant capacity is 25187 MW. The Figure 2 presents energy share by different fuels and resources. Gas provides highest percentage (45%), followed by heavy fuel oil (HFO) and high-speed diesel (HSD). Solar, wind, hydro, biogas, and biomass produces only 3% of demand [10]. The power system master plan intends to raise the proportion of sustainable energy to 10% by 2030. Over the last few decades, inefficient power generation is hindering the rapid economic growth [11]. Furthermore, the large-scale grid connection is not available here. As a result, available energy resources can be utilized in a sustainable manner for the overall development of Kutubdia island, as well as to meet the country's renewable energy targets.

Meanwhile, the national and international organizations are concerned with analyzing sustainable indicators that meet current demand without compromising the future needs [12]. By 2030, the sustainable development goal 7 (SDG7) ensures that everyone has access to affordable, safe, sustainable, and modernized energy [13]. Developing countries are already building infrastructure and upgrading technology to provide modern and sustainable energy services to all sectors, including small islands. Despite rising fuel costs, nonrenewable resources such as coal, oil, natural gas, and uranium will almost probably be consumed within 100 years [14]. However, the primary goal of world leaders is strongly intertwined to energy. Restricting the expansion of energy sector is not a smart plan for maintaining a balance between economic growth and life quality [15]. To tackle global challenges such as climate change, increasing energy consumption, and energy security, world leaders are enacting policies and establishing support mechanisms for renewable energy markets [16]. For many years, researchers have proved the benefits of microgrids. It has accelerated the utility sector's transition to an automated system [17]. Microgrids are still a minority option due to high energy cost [18]. Sound knowledge of microgrid technology is required in this context for project evaluation. Its advancement is heavily reliant on judgement of technical, economic, and regulatory factors [19]. It is impractical to evaluate all types of impacts, components, and characteristics [20]. Researchers usually adapt specific targets to develop their preferred set of indicators in a framework since there is no established methodology for assessing the energy sector's sustainability [21]. The design of sustainable microgrids in developing nations has become increasingly complicated due to the incorporation of diverse evaluation metrics such as renewable expansion, stakeholders, social, and cultural issues. The most comprehensive tool for analyzing sustainability is the life cycle analysis (LCA) of microgrid [22]. Multi-criteria decision analysis (MCDA) was applied in Egypt to rank seven power generation technologies by tying stakeholders to sustainability [23]. Natural gas came in first, followed by renewables and nuclear power, with coal listed in last. To assess LCA, a comprehensive weighted sum method ranked 13 electricity generation technologies based on 10 sets of indicators, revealing that large hydroelectricity is the most sustainable, followed by small hydro, onshore wind, and PV [24]. Other authors put equal emphasis on sustainable criteria for national development, concluding that wind turbines are the most sustainable, followed by hydropower, photovoltaic, and geothermal [25]. The paper applied the analytic hierarchy process (AHP), which considered financial, technical, environmental, and socioeconomic-political issues [26]. The top non-renewable sources are gas and oil, with renewable energy technologies populating the rest. Combining an electricity market model with a subsequent MDCA the best-ranking electricity scenario for Tunisian stakeholders was selected, consisting of 15% wind, 15% solar, and 70% natural gas-generated electricity in the national power mix by 2030 [27]. The sustainability index evaluation for electricity generation varies from model to model due to the lack of an acceptable generalized model [28]. As a result, multiple methods must be used to assess the sustainable microgrid, which assists energy policymakers in making decision about future power generation technologies while ensuring overall sustainable development. In rural areas, policies in developing countries will be restructured to meet modern energy needs at disintegrated levels, necessitating a better evaluation in conjunction with numerous benchmarks [29]. MCDM model is the best suited for such a revolutionary goal. The relative sustainability of energy sources is influenced by region, indicators, and investor perceptions [20]. They developed a framework that public and private investors interested in Brazilian concerns can use. The study assesses and quantify the energy market's sustainability and reliability in Northwestern Europe (France, Germany, Belgium, and Netherlands) [30]. It indicates that a power network including fossil-fueled microgrids and a CO_2 emission has the greatest composite sustainability index. Building new sustainable microgrids is a practical and cost-effective alternative to conventional central-station, which would require additional transmission and distribution infrastructure investments [19]. In Algeria, social and environmental issues were the most significant factors when evaluating sustainable energy against 13 sub-criterions [31]. Solar energy outperformed wind farms, which was followed by biomass, geo-thermal, and hydropower. Despite Saudi Arabia having the world's highest oil production, solar PV, concentrated solar, and wind plant are the most promising technologies, according to the AHP approach [32]. The sustainability study of PV/Wind/Diesel/Battery microgrid was conducted and implemented in northwestern Venezuela utilizing PV for base load and wind meeting the peak demand [18]. For rural and hilly parts of India, a bi-level framework known as decision making and optimization tools was constructed using locally accessible renewable resources that can efficiently fulfill current and future growing demand through sustainable microgrid [33]. An integrated decision-making technique for optimal planning was developed in a rural area of Pakistan, where electricity is generated from renewable sources made up of solar, wind, hydro, and biomass [34]. Hybrid MDCM was developed for Bangladesh's electricity system, keeping in mind five sustainability criteria and expert opinions that were analyzed qualitatively and quantitatively [35]. When considering low-income communities as the most critical factor, the Solar/Wind mixture is the best off-grid choice. The authors used fuzzy logic to rank clean energy for Turkey: wind, solar, hydraulic, biomass, geothermal, wave, and hydrogen, while wind being the best solution [36]. The authors presented a Himalayan microgrid that is sustainable [37]. However, due to the changing microgrid size, the weightage of criterion should be adjusted. The literatures used MDCA-based grey AHP to generate the weighted aggregated sum product of all criterions to identify possible renewable sources for Vietnam [38]. Solar was the most efficient energy source, followed by wind, biomass, and solid waste.

TABLE 1. Research gap between past and our proposed microgrid system in Kutubdia Island.

Considered configuration	MG selection criterion	Year	Ref.
Wind/PV/DEG	✓ Net present cost ✓ Cost of energy	2010	[1]
Wind/Solar/DEG	✓ Net present cost	2013	[6]
PV/Wind/Biogas	✓ Cost of energy	2016	[7]
Tidal/wind/DEG	✓ Net present cost ✓ Cost of energy	2014	[39]
Solar/Fuel	✓ Net present cost ✓ Cost of energy	2018	[9]
PV/Wind/Biogas/DEG	✓ Cost of electricity	2018	[11]
PV/DEG & Wind/DEG	✓ Payback period ✓ Energy cost	2016	[40]
Solar/Diesel	✓ Cost of energy	2018	[41]
PV/Wind	✓ Cost of energy	2016	[42]
Wind/Diesel	✓ Emissions ✓ Life cycle costs	2012	[43]
PV/Wind/Diesel/Battery (Our proposed microgrid)	✓ LCoE ✓ Initial investment ✓ O & M cost ✓ Return on investment ✓ CO_2 emissions ✓ Renewable fraction ✓ Land usage ✓ Ecosystem balance ✓ Excess electricity ✓ Unmet load ✓ Future of technology ✓ Job creation ✓ Comfortable life	Our research will include 4 KSPI and 13 sub-indicators for microgrid selection. Whereas, the past research did not consider four dimensions of sustainability.	

However, several studies that have been conducted on Kutubdia island to meet the load demand using a microgrid system is shown in Table 1. According to the researchers, Wind/PV/Diesel microgrid is feasible solution without any capacity shortage [1]. Utilizing local wind speed and solar irradiation of Island, the energy production cost was 0.175$/kWh for Wind/Solar/Diesel microgrid system [6]. Environmental effects such as carbon dioxide, sulfur dioxide, and nitrogen oxides were also minimized. The authors suggested a Solar/Wind/Biogas configuration with diesel generator as backup and battery to facilitate energy storage [7]. The large-scale power generation using only tidal or wind turbines is not economically a feasible option [39]. Thus, these two-energy system can be combined for cost-effective energy supply. A stand-alone Solar/Fuel Cell minigrid designed to meet energy demands in a sustainable manner [9]. Due to the intermittent nature of renewable resources, three fuel cells were added to ensure an uninterrupted power supply. Wind/Diesel, on the other hand, is suitable with an annual capacity shortage of 5% in any location, resulting in a 20% reduction in energy cost and fuel consumption, as well as a reduction in greenhouse gases (GHG). The microgrid is comprised of PV array, diesel engine generator, biogas generator, and wind turbine that was optimized by HOMER to meet the electricity demand, with a CoE of 0.221 $/kWh [11]. Two hybrid microgrid systems, PV/Diesel and Wind/Diesel were compared using HOMER and RETScreen [40]. The PV/Diesel architecture was preferable over Wind/Diesel in terms of payback period and energy cost. The system generated 97% renewable energy and estimated cost of electricity is 0.420 $/kWh considering 10% rate of return, and investment cost of 199,54$. A cost-effective Solar/Diesel minigrid is designed to meet the energy demands in a reliable manner to ensure uninterrupted power supply, and a fixed capacity diesel generator is added to the system [41]. Different suppliers has been selected of integrated energy system for each string without affecting overall performance, individual string power output can be monitored, and efficient processing units can be singled out [42]. A low-cost off-grid Wind/Diesel hybrid power system was designed for remote Kutubdia [43]. Wind turbines was integrated with traditional diesel generator for supplying power to remote area which significantly reduces the harmful CO_2 emissions and life cycle costs of the microgrid. The proposed electricity production cost was 0.209 $/kWh.

The main focus of the existing research was a techno-economic evaluation of independent microgrid using HOMER software. The four dimensions of sustainability within microgrid named economy, environment, technology, and society was ignored to meet the electricity demand in Kutubdia Island of Bangladesh. While considering sustainability in the context of Bangladesh's Kutubdia Island, throughout literature analysis, the following issues and research gaps are identified.

- To the best of the author's knowledge, no previous study on sustainable microgrid for Kutubdia Island has been conducted. Despite the fact that this type of research is being conducted in various parts of the world in their own unique way.
- A microgrid is driven by locally available resources and benefits to residents, which are heavily influenced by an island's geography. As a result, selection of suitable sustainable microgrid configuration on Kutubdia Island is important.
- Finding the weight of each sustainable indicator is difficult, which complicates aggregated microgrid scoring and ranking. The rule base weight conversion of KSPI from linguistic concepts to numerical value can be convenient to understand for policymakers, but it has not yet been well-developed.

The primary goal of present study is to fill a gap in previous research that proposes methodology for selecting a sustainable microgrid configuration in Kutubdia Island. The following points are the key contributions of this work that distinguish itself from earlier studies:

- In the context of Kutubdia Island, a model framework for microgrid ranking and selection process is proposed by taking four key features of sustainability into account: economy, environment, technology, and society.
- A total of thirteen sub-indicators are included under four KSPI; i.e., economy: cost of energy, initial investment, operation and maintenance, return on investment; environment: CO_2 emissions, land requirements, renewable fraction, ecosystem balance; technology: unmet load, excess electricity, future of technology; society: job creation, and comfort-able life.
- Seven microgrid configurations consisting of solar PV, wind turbine, diesel engine generator, bidirectional converter, and battery are optimized and analyzed.
- In the fuzzy membership functions, the value of each key indicator of sustainability is conveyed in language terms, allowing policymakers to recognize its significance. The ambiguity about the proper weight of the KSPI would be resolved as a result of using a fuzzy controller, and comprehensive sustainability score of the microgrid will be easily determined.

The followings are the assumptions and defined terms used in this research papers:

- Priority denotes that its significance is high, while the weightage of the other three indicators is low. For example, economic priority means economy will be considered as the higher priority over the environment, technology, and society. That is, the term of economy carries more weightage than the other three KSPIs. Environmental, technological, and social priorities are all defined in the similar way as economic priority.
- The priority of the KSPI is driven by economic status of a region defined as low, lower-middle, upper-middle, or high-income by the World Bank. In a low-income country, for illustration, economic priority will be given top consideration while installing a microgrid. When it comes to a developed nation, technology may be the most important factor. As a result, our methodology can be used to pick any type of priority within the aforementioned KSPI.

The paper is organized into fourteen-sections. The first section contains the introduction, which includes information on Kutubdia Island, the study background, the problem statement, the research aims and contribution, and assumptions of study. Section II illustrates the research methodology. The Section III shows resource assessment. Section IV estimates the load profiles, while Section V introduces HOMER Pro software. Section VI gives details modeling of the studied microgrid components and economic parameters, whereas Section VII discusses the four KSPIs along with associated sub-indicators. Section VIII presents seven microgrid configuration, data and model input. Section IX shows sub-indicators determination by HOMER optimization, and assigning a value with relative scale of preferences. Section X explains normalization process of sub-indicators and necessary statistical formula. Section XI explains the fuzzy logic scoring process of sustainable microgrid. Section XII compares and ranked the microgrids based on fuzzy rules Section XIII discusses electrical, financial, emissions and sensitivity analysis of selected sustainable MG. Finally, Section XIV concludes this paper.

II. RESEARCH METHODOLOGY

The methodology used in order to achieve the goals of this research is presented in Figure 3. The preceding section provides a comprehensive literature review in order to identify the research gaps. The site of Kutubdia Island has been chosen as the study location. The meteorological data, such as sun irradiation and wind velocity parameters, is collected. As a fuel, diesel has been used, which is a non-renewable resource. The daily electric load is determined based on the two major seasons of winter and summer. Under the HOMER framework, the components of the microgrid as well as economic aspects, are mathematically modelled. The software allows use of the necessary component and

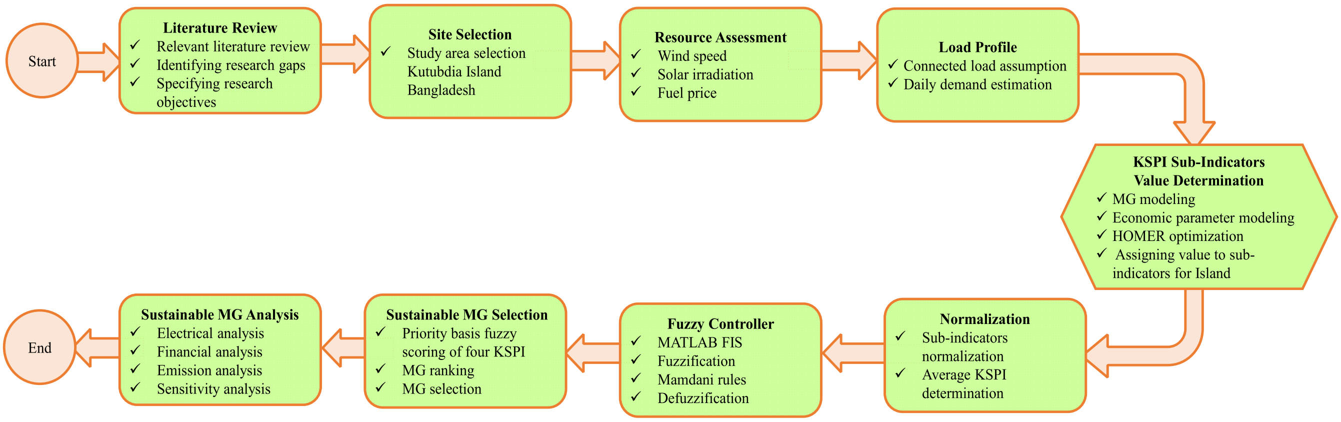


FIGURE 3. Research methodology.

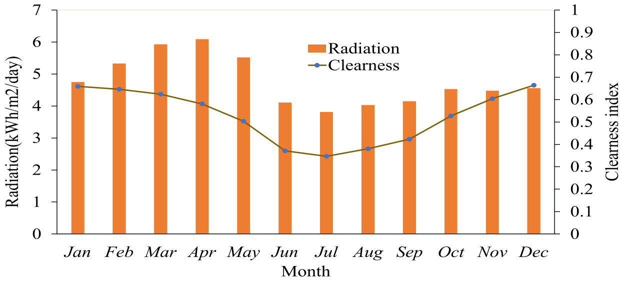


FIGURE 4. Global horizontal irradiation.

constraint model data for off-grid microgrid applications. The load following approach is used to optimize seven different hybrid system based on the lowest net present cost. Each hybrid system is solved to meet the required load demand and also a number of technical and environmental limitations, such as capacity constraints, battery characteristics, spinning reserve, and so on. The cost of energy, initial investment, operation and maintenance costs, return on investment, CO_2 emissions, renewable fractions, excess power, and unmet load are among the eight sub-indicators of sustainability calculated by HOMER. In addition, relative numerical values are assigned to the following five sub-criteria for a more comprehensive analysis: land usage, ecological balance, future of technology, employment generation, and comfortable life. As a result, the overall 13 sub-indicators' normalized values, as well as the average value of the KSPI, are computed. To determine the score of each priority parameter of the KSPI, fuzzy logic Mamdani rules are designed. Finally, the integrated score is computed using the MATLAB fuzzy inference system. The sustainability of seven microgrid topologies are compared, and the one with the highest score is ranked first, and chosen for the Island. Furthermore, the influential parameter named electrical, financial, emission and sensitivity are also analyzed for a selected microgrid.

III. ENERGY RESOURCE ASSESSMENT

Kutubdia could be a viable candidate for utilizing renewable energy resources. This island has been found to be suitable for generating electricity using wind energy, and accordingly Bangladesh government has already installed a wind mill there. Throughout the year, the island receives moderate solar radiation, making it suitable for generating electricity with solar PV panels. HOMER utilizes the monthly wind speed and solar irradiation data for Kutubdia Island from the National Aeronautics and Space Administration (NASA). Figure 4 depicts the average monthly solar radiation profile, which has a scaled annual average radiation of 4.774 kWh/m^2/day and a clearness index of 0.527. In the months of February to May, incident solar irradiation is high in Kutubdia. Figure 5 depicts the annual wind speed profile, with an average wind speed of 4.77m/s at a 50 m anemometer height. The diurnal pattern strength of 0.25 has been taken into account, and 14.00 is the windiest time of day. Kutubdia has a Weibull shape factor of 2.00. Figure 6 illustrates a wind speed histogram and this data extracted from HOMER to determine the yearly variation of wind characteristics.

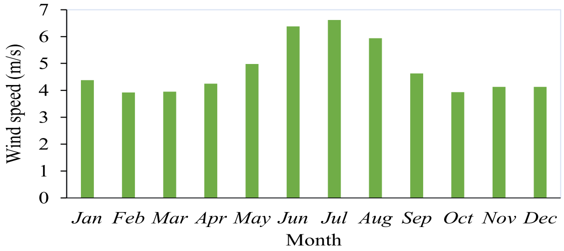


FIGURE 5. Wind speed.

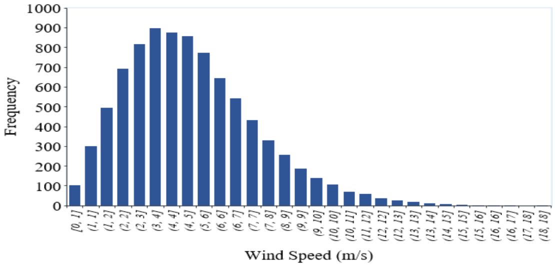


FIGURE 6. Wind speed histogram at Kutubdia Island.

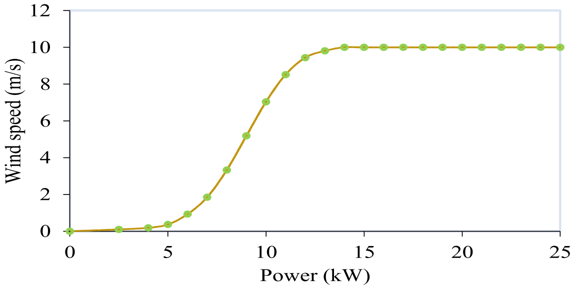


FIGURE 7. **Wind turbine power curve.**

Figure 7 presents appropriate turbine characteristics for Kutubdia Island. Diesel is a very common fuel that is widely used in remote power generation as renewable energy has intermittence nature. Despite the difficulty of transporting diesel, it is used to generate electricity in Kutubdia to increase the reliability of the supply system. But emissions of pollutants have to be limited. For this study, diesel with a lower heating value of 43.2 MJ/kg and a price of $0.91 $/L was considered.

IV. LOAD ESTIMATION

A community of 2000 families, ten hotels and resorts, ten educational institutes, ten super-markets, one medical center (Hospital), one ice factory, and one EV charging station are considered as connected loads for Kutubdia Island. Table 2 presents the details of load category, equipment ratings, quantity etc. The income of every family is not the same. According to their load consumption, households are classified as high-, middle- and low-income group. A high-income family's domestic load includes a light, fan, TV, fridge, and water-pump. A middle-class family does not have a washing machine or a water pump. The load demand for the educational institutes is between 8:00 and 17:00 hours. The super shops open from morning to mid-night. The light, fan and motor are the main load of shops area. In order to provide emergency services, the medical center must always be connected as a critical load. Furthermore, the ice-making factory runs 24 hours a day and seven days a week because fishing is the islanders' primary occupation. The estimated loads are divided into two seasons: winter (November-February) and summer (March-October). Figure 8 depicts the load profile of two seasons according to probable load consumption of the community. Because of the cold weather, fans are not used during the winter. As a result, after midnight, demand is extremely low. In both seasons, the peak demand is in between 21:00 and 23:00 hours. Following the load calculation, the scaled annual average load in HOMER is determined to be 14,948 kWh/day, with a day-to-day random variability of 10% and a peak load of 1458.9 kW. The load factor is 0.430.

V. HOMER PRO OPTIMIZATION

Researchers have used various tools over the last few decades to analyze the technical, economic, environmental, and socio-political aspects of various renewable energy technologies. It is proved that the majority of these studies were carried out using optimization tools called Hybrid Optimization of Multiple Energy Resources (HOMER). The National Renewable Energy Laboratory, United States developed the software. It is widely applied in the field of HRES sizing and optimization due to its accuracy, simplicity, and rapidity. Also, the tools were chosen because of its ability to perform both financial and technical analysis, as well as its availability and widespread acceptance for on/off-grid microgrid modeling, despite the fact that learning all of its features takes time [44]. Figure 9 demonstrates the general flow diagram of the Homer Pro software. After providing inputs such as resource data, load profile, economic data, microgrid constrains and control strategy, it will optimize the hybrid system and give various outputs such as lowest net present cost, component size, cost of energy, excess electricity, unmet load, return on investment, and other factors as the optimization results. In broad strokes, the entire system of is modeled using two approaches: components modeling and economical aspects modeling. The system components assist in projecting net electricity production, whereas the economic model assists in determining whether a proposed model is feasible or not. There is always a trade-off between the production of electricity and the cost associated during microgrid project life. As a result, to determine the best configuration, renewable energy ratio, and optimal size of the proposed microgrid, and system output variables are compared to economic parameters. The software uses several control strategies of microgrid power management. The outcome of optimal hybridized system configurations is significantly influenced by power management strategy [45]. The selection of optimal sizing generally requires a detailed analysis of available renewable energy resources, system hardware components, and an appropriate operating strategy. The majority of studies on hybrid energy systems reported in the literature used a load following strategy for system sizing and performance analysis.

VI. MICROGRID COMPONENT MODELING

A simplified block diagram of the studied microgrid (MG), as well as the equipment and their interrelationships are presented in Figure 10. The MG is comprised up of solar panels, a wind turbine generator (WTG), a diesel engine generator (DEG), battery storage units, a converter, and consumers. Direct current power is provided by battery storage devices and solar PV modules. When load demand is low, the battery stores excess energy. Before being linked to the AC bus bar, the DC supply from the PV and batteries is converted to alternating current (AC) using bidirectional converters. The DEG and WTG generate AC power. As a result, it is connected to the AC bus bar directly. The AC loads are fed from the AC bus bar, and no DC loads are considered in this study. The diesel generator serves as a backup when renewable energy sources are insufficient.

TABLE 2. Connected load profile.

SI	Load category		Appliances	Size (W)	Quantity	Total number	Connected load (kW)
1.	Domestic load	High income	Light	40	6	500	120
			Fan	70	3		105
			TV	20	1		10
			Fridge	80	1		40
			Washing machine	500	1		250
			Motor-pump	1000	1		500
		Middle income	Light	40	3	1000	120
			Fan	70	2		140
			TV	20	1		20
		Low income	Light	40	2	500	40
			Fan	70	1		35
2.	Residential hotel and resort		Light	40	50	10	20
			Fan	70	20		14
			TV	20	10		2
			Motor-pump	2000	2		40
3.	Educational institutes		Light	40	50	10	20
			Fan	70	20		14
			Motor-pump	2000	2		40
4.	Super-shops		Light	40	10	10	4
			Fan	70	5		3.5
			TV	20	1		0.2
			Motor-pump	1000	1		10
5.	Medical and hospitals		Light	40	100	1	4
			Fan	70	20		1.4
			Fridge	1000	1		1
			Motor-pump	5000	1		5
6.	Ice making factory			10000	1	1	10
7.	EV charging station			5000	1	1	5
Total connected load							1574.1

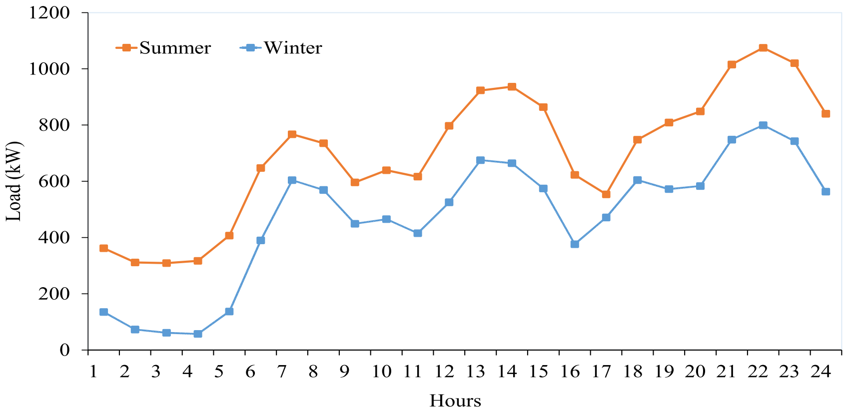


FIGURE 8. Daily load profile for summer and winter season.

The various components of a microgrid that can be modeled using HOMER software are described below.

A. SOLAR PV

The performance of a solar PV module changes due to numerous environmental conditions (e.g., temperature, wind speed). Annual output energy panels can increase with 0.1% °C increase in the temperature coefficient. The PV output depends on solar irradiation incident during the day and is estimated on an hourly basis using the Eq (1) [46]–[55].

$$P_{PV}(t) = Y_{PV} f_{PV} \times \frac{G_{PV}(t)}{G_{ref}}\left[1 + \alpha_P\left(T_{PV}(t) - T_{ref}\right)\right] \quad (1)$$

where Y_{PV} (kW) = rated capacity of PV array, f_{PV} (%) = derating factor, G_{PV} (kW/m^2) = solar irradiation incident on the PV array, G_{ref}(kW/m^2) = incident solar irradiation

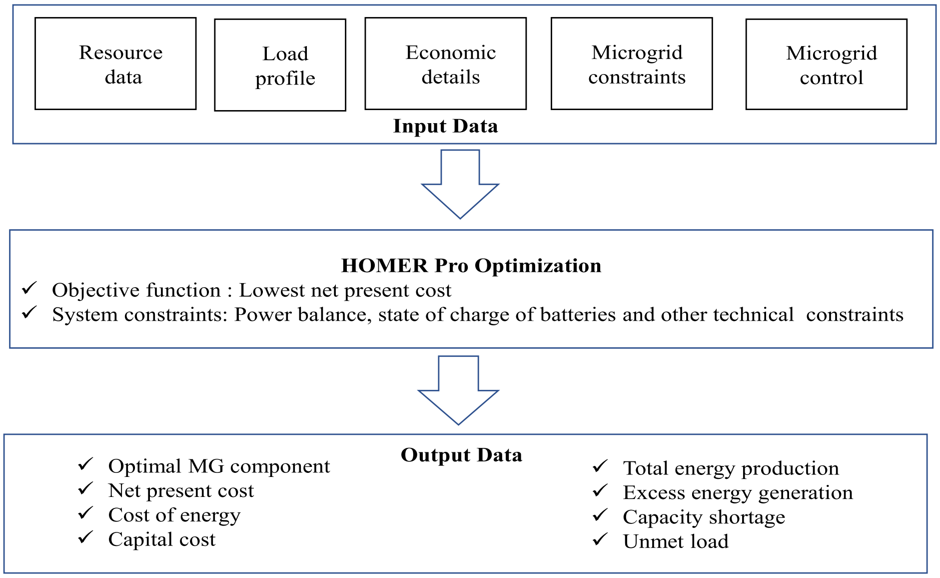


FIGURE 9. Flowchart of HOMER Pro software framework.

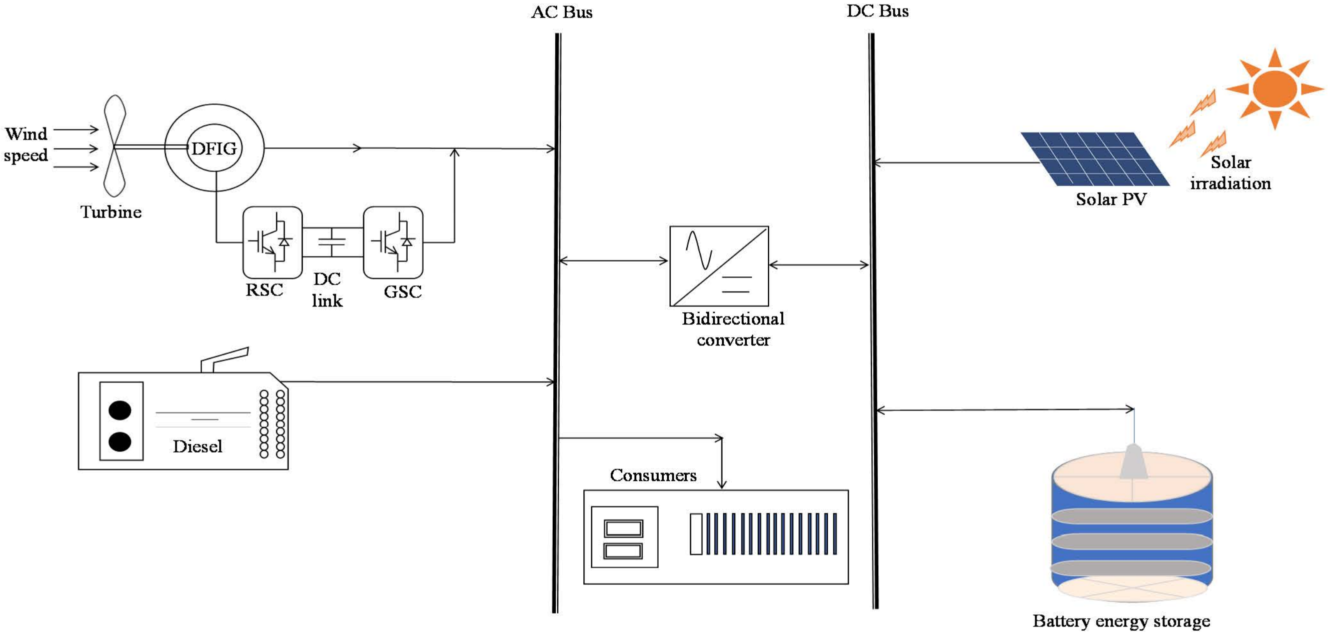


FIGURE 10. Studied microgrid system.

at standard test conditions, α_P = temperature coefficient of power, T_{PV}(°C) = PV cell temperature, and T_{ref} (°C) = PV cell temperature under standard test conditions at 25°C. The derating factor accounts for output power reductions caused by various environmental conditions, such as dust accumulation on the panel surface, aging, wiring loss, and shading.

The cell temperature T_c(°C) can be calculated from the energy balance of the PV module using Eq.(2) [50].

$$(\tau\alpha)\, I_T = \eta_{PV} I_T + U_L\,(T_c - T_a) \tag{2}$$

where $(\tau\alpha)$ = effective transmittance-absorptance of PV array, η_{PV} (%) = PV panel efficiency, U_L (kW/m^2°C) = heat transfer coefficient, and T_a (°C) = ambient temperature. Eq. (2) can be rewritten as follows:

$$T_c = T_a + I_T\left(\frac{\tau\alpha}{U_L}\right)\left(1 - \frac{\eta_{PV}}{\tau\alpha}\right) \tag{3}$$

However, the value of $\left(\frac{\tau\alpha}{U_L}\right)$ is difficult to measure, it is based on the manufacturer's report on the nominal operating cell temperature (NOCT), which results at 800W/m^2 solar irradiation, at 20°C ambient temperature, and no load condition (i.e., $\eta_{PV} = 0$). The Eq. (3) can be rewritten as follows:

$$\left(\frac{\tau\alpha}{U_L}\right) = \frac{T_{c,NOCT} - T_{a,NOCT}}{I_{T,NOCT}} \tag{4}$$

The final PV cell temperature can be calculated using the following Equation, with HOMER assuming a value of $(\tau\alpha)$ of 0.9 [50], [51]

$$T_c = T_a + I_T \frac{T_{c,NOCT} - T_{a,NOCT}}{I_{T,NOCT}} \left(1 - \frac{\eta_{PV}}{0.9}\right) \tag{5}$$

There are no tracking arrangements in this system, and a 90% derating factor for each panel is taken into account due to the changing effects of temperature and debris on the solar panels.

Eq.(6) gives the total power generation by the (N) number of PV module at any time (t) [48].

$$P_{TPV} = N_{PV} \times P_{PV}(t) \tag{6}$$

B. WIND TURBINE

HOMER uses three-steps to determine the wind turbine's output at each time step. First, HOMER calculates the wind speed at the hub height of the wind turbine. The output power of the wind turbine is then computed using that wind speed and standard air density. Finally, it adjusts the output value to compensate for the actual air density. The power law, described by Eq.(7), determines the wind velocity at any height (H) [46]–[48], [50]–[51]:

$$v(t) = v_{ref}(t) \times \left(\frac{H}{H_{ref}}\right)^{\gamma} \tag{7}$$

where v_{ref} = reference velocity recorded at the reference hub height (h_{ref}), and γ refers to the power law exponent [48]. The two-parameter Weibull distribution is widely used to characterize wind regimes, which varies between 0.10 and 0.25 [54].

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \times exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{8}$$

v = wind speed [m/s]
k = Weibull shape factor [unitless]
c = Weibull scale parameter [m/s].

The cumulative distribution function (CDF) is given by equation below:

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{9}$$

The equation below connects the two Weibull parameters and the average wind speed.

$$\bar{v} = c\Gamma\left(\frac{1}{k} + 1\right) \tag{10}$$

where Γ = the gamma function.

The energy generation from the wind turbine varies significantly due to highly variable wind velocity. The wind turbine output is computed by Eq.(11) [46], [48], [49],

$$P_{WT}(t) = \begin{cases} 0 & v(t) \le v_{cut-in} \\ P_r \times \left(\dfrac{v^3(t) - v^3_{cut-in}}{v^3_r - v^3_{cut-in}}\right) & v_{cut-in} < v(t) < v_r \\ P_r & v_r < v(t) \ge v_{cut-out} \\ 0 & v(t) \ge v_{cut-out} \end{cases} \tag{11}$$

where, wind velocity, rated wind velocity, cut-in wind velocity, and cut-out wind velocity are denoted by $v(t)$, v_r, v_{cut-in}, and $v_{cut-out}$, respectively. Furthermore, P_r denotes the rated turbine power. The total power production by N number of wind turbines can be represented by Eq.(12) [48]

$$P_{TWT} = N_{WT} \times P_{WT}(t) \tag{12}$$

C. DIESEL ENGINE GENERATOR

The marginal fuel consumption of the generator is represented by the slope of the generator fuel curve. The fuel curve slope is determined by plotting a straight line of fuel consumption versus generator power output. HOMER determines the fuel consumption rate for a certain time step if the generator is running [47], [54]:

$$F = F_0.Y_{gen} + F_1.P_{gen} \tag{13}$$

where
F = rate of fuel consumption at this time step [L/hr]
F_0 = intercept coefficient of the generator fuel curve [L/hr/kW rated]
F_1 = slope of the generator fuel curve [L/hr/kW output]
Y_{gen} = generator rated capacity [kW]
P_{gen} = generator output in this time step [kW].

If the generator is not running in a given time step, the fuel consumption is zero for that time step.

D. BATTERY

Lead-acid battery is used in this study. It stores surplus energy during charging and delivers energy when RE sources are inadequate. Eq.(14) gives the maximum amount of power stored by battery [46], [47], [49]–[52]:

$$P_b(t) = \frac{kQ_s(t)e^{-k} + Q(t)kc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - e^{-k\Delta t}\right)} \tag{14}$$

where Q_s(t) = available energy at the start of the time step and above the minimum state of charge (B_{SOCmin} = 20% for lead-acid battery), Q(t) = total energy at the start of the time step, c = storage capacity ratio, Δt = storage rate constant, and t = time step length. Eq.(15) can be used to calculate the maximum battery discharge power [46], [47], [49]–[52]:

$$P_b(t) = \frac{-kcQ_{max} + kQ_s(t)e^{-k\Delta t} + Q(t)kc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \tag{15}$$

where Q_{max} = storage's maximum capacity.

Eq.(16) and (17) compute available battery energy while charging and discharging at every time step [48].

$$E_b(t) = E_b(t-1)\times(1-\sigma)+\left[E_G(t)-\frac{E_L(t)}{\eta_{inv}}\right]\times\eta_b \quad (16)$$

$$E_b(t) = E_b(t-1)\times(1-\sigma)-[\frac{E_L(t)}{\eta_{inv}}-E_G(t) \quad (17)$$

The battery energy at time (t) and $(t-1)$ is $E_b(t)$ and $E_b(t-1)$. Σ = self-discharge rate. Whereas η_{inv} and η_b stand for inverter and battery efficiency, respectively. The total energy generation, $E_G(t)$, from renewables is calculated using Eq.(18) [48]

$$E_G(t) = N_{PV}\times P_{PV}(t) + N_{WT}\times P_{WT}(t) + N_{DEG}\times P_{DEG}(t) \quad (18)$$

The battery bank's state of charge is expressed as follows [48]:

$$B_{SOC}(t) = \frac{E_b(t)}{E_{b,max}} \quad (19)$$

The number of years or charge/discharge cycles can be used to calculate the battery's lifetime.

E. BIDIRECTIONAL CONVERTER

Since the solar PV and battery bank provide DC power while the demand is in AC mode, a bidirectional converter is used to convert DC power to AC power or vice versa. HOMER utilizes Eq.(20) to calculate the size of the converter depending on the energy flow throughout the buses [46]–[49].

$$P_o(t) = \eta_{inv}\times P_i(t) \quad (20)$$

where $P_o(t)$ and $P_i(t)$ is the output and input power of the inverter respectively.

F. ECONOMIC PARAMETERS

1) COST OF ENERGY

The optimal sizing is found based on the lowest CoE of the microgrid architecture. The CoE is calculated by HOMER using Eq. (21) [49], [52], [54].

$$CoE = \frac{C_{ACC}+C_{ARC}+C_{AOM}}{C_{AES}} \quad (21)$$

where, C_{ACC} = Capital cost on an annualized basis
C_{ARC} = Cost of replacement over a year
C_{AOM} = Annualized cost of operation and maintenance
E_{AES} = Yearly electricity served.

2) NET PRESENT COST

The net present cost (NPC), on the other hand, is computed using Eq.(22), where $CRF(i, n)$ is the capital recovery factor, which may be obtained using Eq.(23) and Eq.(24) [49], [54].

$$NPC = \frac{C_{ACC}+C_{ARC}+C_{AOM}}{CRF(i,n)} \quad (22)$$

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n-1} \quad (23)$$

$$i = \frac{i'-f}{i'+f} \quad (24)$$

where n = number of years and i = real annual interest rate, as determined by Eq. (23). The nominal interest rate is i' and the yearly inflation rate is f. The current research uses an 8% nominal discount rate and a potential inflation rate of 3%.

3) CAPACITY SHORTAGE FRACTION

The capacity shortage fraction equals to the total capacity shortage divided by the total electrical demand. The capacity shortage fraction must be less than or equal to the maximum yearly capacity shortage for a system to be considered acceptable by HOMER and calculated by using the following equation [54]:

$$f_{cs} = \frac{E_{cs}}{E_{Demand}} \quad (25)$$

where, E_{cs} = total capacity shortage (kWh/yr)
E_{Demand} = total electrical demand (kWh/yr).

4) UNMET LOAD FRACTION

The percentage of total annual electrical load that remains unfulfilled due to insufficient generation is known as the unmet load fraction [54]:

$$f_{Unmet} = \frac{E_{Unmet}}{E_{Demand}} \quad (26)$$

where, E_{Unmet} = total unmet load (kWh/yr)
E_{Demand} = total annual electrical demand (kWh/yr).

5) EXCESS ELECTRICITY FRACTION

The ratio of total excess electricity to total electricity production is known as the excess electricity fraction. The following equation is used by HOMER to calculate this value at the end of each simulation [54]:

$$f_{Excess} = \frac{E_{Excess}}{E_{Prod}} \quad (27)$$

where, E_{Excess} = total excess electricity (kWh/yr)
E_{Prod} = total electrical production (kWh/yr).

VII. SUSTAINABILITY DIMENSIONS

The four indicators of sustainable microgrid are economy, environment, technology, and society. As can be seen in Figure 11, they are also separated into sub-indicators. In this section, total 13 sets of such identified parameters are discussed below.

A. ECONOMY

Cost of Electricity: The price of energy offered by a hybrid microgrid includes all expenditures incurred throughout the lifetime, such as the initial investment, operating and maintenance costs, fuel pricing, and so on. It is also influenced by the typical characteristics of the technology,

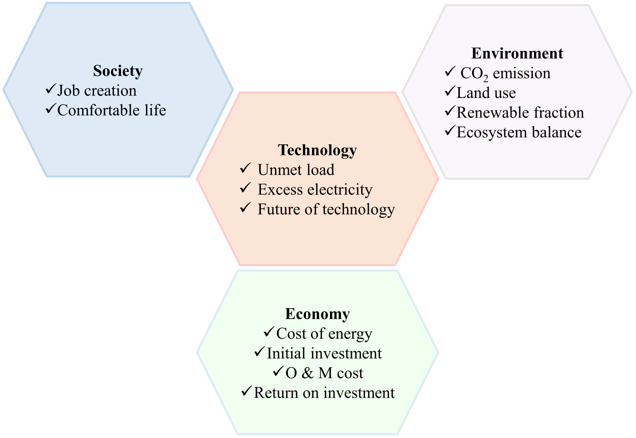


FIGURE 11. Sustainable microgrid indicators.

such as efficiency, annual energy production, and service life, as well as the type of energy resources involved [23], [25].

Operation and Maintenance Cost: Salaries, fuel costs, engineering and consultation services, and money that is spent on system maintenance, buying spare components, all contribute to the total cost of operation and maintenance. Basically, Maintaining the system on a regular basis is much less expensive than repairing any damage [22], [23], [56].

Investment Cost: All costs associated with the building and installation of power plants, procured equipment, engineering and consultation services, and any costs that may emerge prior to the power plants' operation are included in the investment cost. The investment expenses and benefits must be considered by the investors. The most common economic criterion for evaluating energy systems is the investment cost [22], [23].

Return on Investment: The annual cost savings compared to the initial investment is known as the return on investment (*RoI*) [54].

B. ENVIRONMENT

CO_2 Emission: The majority of CO_2 emissions come from the combustion of fossil fuels, which are made up of hydrocarbons. Many international organizations have recently expressed concern about climate change and are working on measures to minimize CO_2 emissions, recognizing this indicator as crucial for assessing sustainability [22], [25].

Land Usage: In this study, land requirements are used as environmental indicators. The use of land for electricity is costly to human settlement, and has both benefits and drawbacks. Land use is assessed during the microgrid lifecycle to make a fair comparison of technologies. Construction, operation, and decommissioning, value of land after resources installation are all included [24], [25].

C. TECHNOLOGY

Unmet load: The demand that the hybrid microgrid system is unable to meet [54].

TABLE 3. Project data.

Parameters	Values
Project life	25 years
Nominal discount rate	8%
Expected inflation rate	3%
Maximum annual capacity shortage	10 %

Excess Electricity: When demand is lower than generation, microgrid surplus power is generated [57]. For off-grid case, the excess power is discarded.

Future of Technology: What is the technology's future? Will it be replaced by other technologies? Will the scope of this technology expand or restricted? Because some technologies or fuels may be particularly resource constrained, the availability and limitations of each technology must be considered [25].

D. SOCIETY

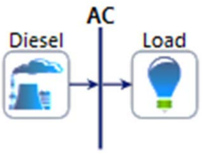
Job Creation: Each component of the microgrid has its own employment creation factor. It increases the community's quality of life while also lowering the unemployment rate. Throughout the microgrid's life cycle, many people are employed, either directly in activities like manufacture, installation, operation, and maintenance, or indirectly in jobs like suppliers of equipment, construction, and installation. Wind energy is available 24 hours a day, however it has higher maintenance than solar energy. As a result, WTG will be able to offer more career opportunities [22]–[24], [55].

Comfortable Life: If power is accessible without interruptions, the community will live in greater comfort. Photovoltaics has been restricted by storage difficulties at night and on cloudy days when the sunlight cannot incident on cells. Wind turbines noise pollution also disturbs the harmony of life. It has negative effects on human psychological health as well as environmental consequences. Noise-induced hearing loss can occur as a result of long-term noise exposure, especially in the working surroundings of the energy plants [22], [25], [26].

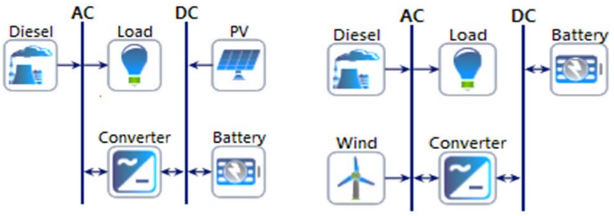
Ecosystem: It evaluates the viability of renewable energy program as well as its environmental impact. Diesel and wind turbines are harmful to the environment [26], [58]. Birds will be struck by the wind turbines.

VIII. MICROGRID SCENERIOS AND MODEL INPUT

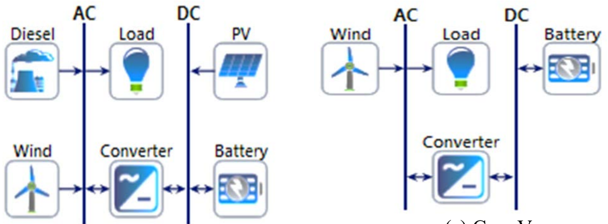
HOMER simulates the off-grid combinations in order to determine lowest cost of energy. Seven configurations of microgrid are considered and optimized as shown in Figure 12. The solar system, wind turbine, diesel engine generator, bi-directional converter, and battery bank are all evaluated as key components of the microgrid. Unit numbers, capital, replacement, operation and maintenance costs, and operating hours must be declared in HOMER before the simulation is run. This project is assessed for a period of 25 years with an interest rate of 8%. Table 3 contains the project's detailed information. 10% maximum annual capacity short-



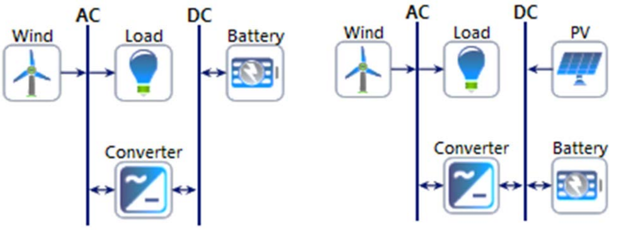
(a) Case I



(b) Case II (c) Case III



(d) Case IV (e) Case V



(f) Case VI (g) Case VII

FIGURE 12. Seven configurations of microgrid.

age is considered for Kutubdia. The data for others component is taken from references [46], [47], [49]–[52] A solar PV module's capital cost is assumed to be 2000 \$/kWp with a 25-year warranty is given in Table 4. Due to robustness, the doubly feed induction generator (DFIG) wind turbine is chosen for analysis. The cost of a wind farm in this paper includes the costs of the turbine, generator, and converter, as well as transportation and installation. A wind farm's capital cost is approximated to be 2500\$/kW. The replacement and operation and maintenance costs are set at 70% and 4% of the total capital cost, respectively. The hub height is considered as 20m. The technical data of wind turbines, diesel generator, bidirectional converter and battery data is shown from Tables 5 to 8, respectively. A generic 6-volt lithium-ion battery with an energy storage capacity of 820Ah/6.91 kWh is used for off-grid analysis.

IX. SUB-INDICATORS DETERMINATION

The sub-indicator's value of four KSPI is determined by two ways. HOMER software can compute eight of the thirteen sub-indicators. On the other hand, a value is assigned to others five sub-indicators in context of Kutubdia Island.

TABLE 4. Solar PV data.

Parameter	Value
Rated power	1 kW
Capital cost	2000 \$/kW
Replacement cost	1340 \$/kW
Operation and maintenance cost	26 \$/year
Lifetime	25 years
Sizes considered	50-10,000 kW, 50kW interval
Derating factor	90%

TABLE 5. Wind turbine data.

Parameter	Value
Rated power	10 kW
Starting wind speed	2.5 m/s
Cut-off wind speed	25 m/s
Hub height	20 m
Weibull k	2
1-hour autocorrelation factor	0.80
Diurnal pattern strength	0.25
Hour of peak windspeed	14
Capital cost	2500 \$/kW
Replacement cost	1750 \$/kW
Operation and maintenance cost	100 \$/year
Lifetime	20 years

TABLE 6. Diesel generator data.

Parameter	Value
Capital cost	370 \$/kW
Replacement cost	296 \$/kW
Operation and maintenance cost	0.03 \$/hour
Operational lifetime	15000 hours
Minimum load ratio	25
Fuel curve intercept	0.014 L/hr./kW_{rated}
Fuel curve slope	0.244 L/hr./$\text{kW}_{\text{output}}$
Capacity	1 kW

TABLE 7. Converter data.

Parameter	Value
Capital cost	800 \$/kW
Replacement cost	750 \$/kW
Operation and maintenance cost	10 \$/year
Lifetime	15 years
Sizes consideration	0-10,000 kW 50kW interval

TABLE 8. Battery data.

Parameter	Value
Nominal voltage	6
Nominal capacity	820Ah/6.91 kWh
Capital cost	1100 \$/kWh
Replacement cost	1000 \$/kWh
Operation and maintenance cost	20 \$/year
Lifetime	15 years
Initial state of charge	90%
Final state of charge	20%

A. SUB-INDICATOR FROM HOMER OPTIMIZATION

Seven hybrid microgrid setups are simulated by HOMER. The simulation takes into account the various capacities of

TABLE 9. Homer optimization results.

MG case	Component size					Cost				RoI (%)	Electricity produced (kWh/yr)	Fuel used (L/yr)	CO_2 emission (kg/yr)	Renewable fraction (%)	Excess electricity (%)	Unmet load (%)
	PV (kW)	Wind (kW)	Diesel (kW)	Converter (kW)	Battery (1kWh)	CoE ($/kWh)	NPC (M$)	Initial capital (M$)	O & M (M$/yr)							
Case I	0	0	1000	0	0	0.331	25.4	0.37	1.75	0	5474244	1458355	3824137	0	1.76	1.43
Case II	2650	0	650	1300	2250	0.281	21	9.06	0.83	6.5	6156936	440266	1154477	68.5	5.81	4.01
Case III	0	11000	750	1000	2050	0.272	20.7	6.08	1.02	8.8	8922586	602348	1579493	57.9	36.2	2.50
Case IV	1250	10500	450	1150	2250	0.236	17.6	8.69	0.62	9.6	9247642	199110	522110	85.8	37.8	4.32
Case V	5650	0	0	1450	4400	0.344	25	17.3	0.54	3.2	9612296	0	0	100	37.3	6.71
Case VI	0	59500	0	1500	3350	0.452	33.3	19.8	0.95	0.2	36137596	0	0	100	84.1	5.56
Case VII	2650	7000	0	1300	3350	0.249	18.4	11.8	0.46	7.3	8759904	0	0	100	33	5.60

PV modules, wind turbines, diesel generators, and batteries. Table 9 shows the optimization outcome. Systems with low energy cost and net present cost, the software selects the appropriate solution. None of the scenarios incorporate grid connection, because this area does not have access to the electrical grid, although a grid-connected hybrid system has a lower energy cost, it will take longer time to develop and has high installation cost. The following sub-sections detail many cases and their outcomes.

- *Case I: Diesel Only*

The very first case considered in this analysis is primarily a diesel generator. The system is only powered by a 1000 kW generator. Table 6 shows that the renewable fraction of this system is zero because no renewable energy resources are connected. The CoE, initial cost, and annual cost were found to be 0.331 $/kWh, 0.37M$, and 1.75M$, respectively. The generator produces 5474244 kWh of electricity per year. A total of 14,58,355L of diesel is required to produce this amount of electricity. This system emits a significant amount of CO_2 into the atmosphere. This is because diesel has a high carbon content, responsible for nearly 88 percent of the total emission. This configuration is not optimal because this techno-economic system is expensive and produces a large amount of CO_2.

- *Case II: PV/Diesel/Converter/Battery*

The second case studied in this analysis is a hybrid PV/Diesel/Converter/Battery system. The system is composed of 2650 kW of solar PV, 650 kW of diesel, a 1300 kW converter, and 2250 battery cells. The COE, initial cost, and operating cost were observed to be 0.281 $/kWh, 9.06 M$, and 0.83 M$, respectively. The total annual electricity production is 6,156,936 kWh/year. The renewable fraction, excess electricity, and unmet load percentages are 68.5 %, 5.81 %, and 4.01 %, respectively.

- *Case III: Wind/Diesel/Converter /Battery*

The third case considered in this analysis is a hybrid wind/diesel/converter/battery microgrid system. The system includes a 11000kW WTG, a 750kW diesel generator, a 1000kW converter, and a 2050 kWh battery. The CoE and initial investment, renewable fraction, and unmet load were lower in Case III than in Case II, but excess electricity and CO_2 emissions were higher. The costs have seemed to be a barrier in the implementation of this system.

- *Case IV: PV/Wind/Diesel/Converter /Battery*

The fourth architecture features all type of components. The optimal component size is 1250kW PV, 10500kW wind turbine, 450kW diesel generator, 1150kW converter, and 2250kWh battery. Overall cost of energy is the cheapest. As a result, consumers can purchase electricity at the lowest possible price. In comparison to the previous three cases, the initial cost is reasonable, and CO_2 emissions are low, while the renewable fraction, excess electricity, and unmet load are all higher. Its operation and maintenance costs, on the other hand, are the second highest.

- *Case V: PV//Converter/Battery*

The fifth scenario has a 5650kW PV system, 1450kW of converter rating, and 4400kWh of battery storage. This system is economically unfavorable due to its high CoE and initial cost, and there is also a considerable amount of extra electricity observed. The unmet load is also the highest. However, with 100% renewable energy, there are no emissions and the operational costs are low.

- *Case VI: Wind/Converter /Battery*

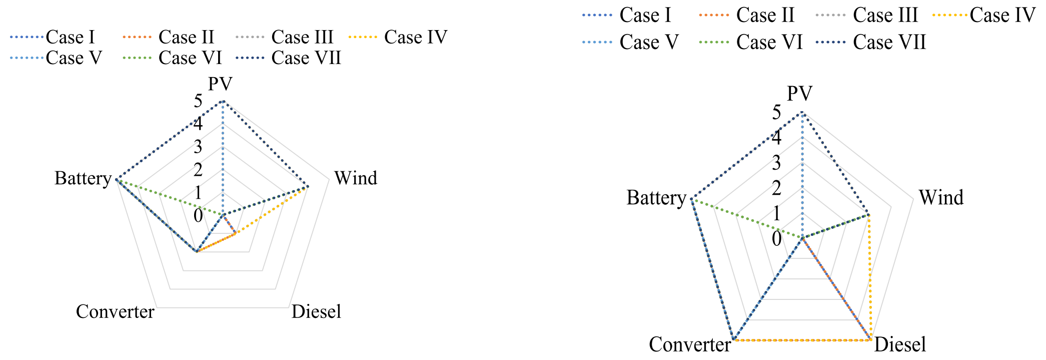
This study has been extended to analyze the Wind/Converter/Battery system. This system consists of a 59500kW wind turbine, a 150kW converter, and a 3350kWh battery. It has the greatest electricity cost of all scenarios, as well as excess electricity generated. This system is not cost-effective. Also, in terms of technology, it has not reached maturity.

- *Case VII: PV/Wind/Converter /Battery*

A 2650kW PV system, a 7000kW wind turbine, a 1300kW converter, and a 3350kWh battery make up this system. It has a cheap energy cost when compared to other hybrid renewable powered energy sources. Currently, researcher from different parts is trying to power off grid area using solar and wind. The considerable amount of initial investment, 11.8 M$, is required for the installation this microgrid.

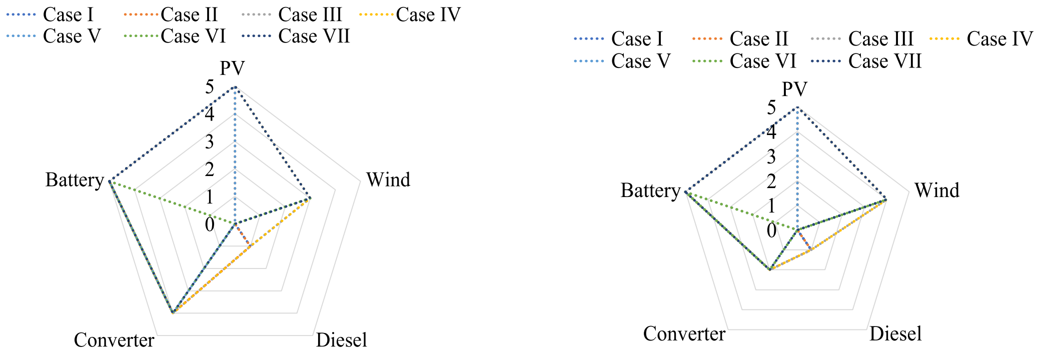
B. ASSIGNING VALUE TO SUB-INDICATORS

Out of 13 sub-indicators considered in this study, HOMER cannot determine the five sub-indicators used in KSPI



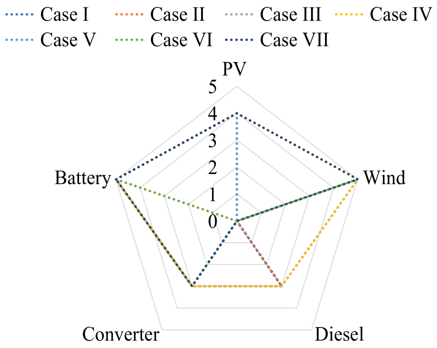
(a) Land use

(b) Ecosystem



(c) Future of Technology

(d) Job creation



(e) Comfortable life

FIGURE 13. Assigning value against sub-indicators of sustainability for Kutubdia Island of Bangladesh.

such as land usage, ecosystem, future of technology, job creation, and comfortable life. The degree of preference can be used to assign a value to the sustainable sub-indicators [16], [23]–[26], and [28]. Table 10 presents the relative preference scale between 0 and 5. The number 1 indicates a weak preference, while the number 5 implies the strongest preference of particular technology. The number zero (0) denotes the absence of a relevant component from the microgrid. Figure 13 depicts the value assigned to each component of the microgrid configurations from the perspective of Kutubdia Island for a specific sub-indicator. A diesel generator requires less space with a preference scale score of 5 although this technology will not be widely deployed in the future. In the literatures, solar PV is frequently regarded as having negative implications for land utilization. There are lots of places in Kutubdia where no crops are grown, thus this panel installation could be beneficial for both land usage, and ecosystem balance. Power from wind turbine is available at all times, so there are chances of no-load shedding, allowing for a comfortable life. However, birds have been known to die as a result of wind turbine strikes. Therefore, it has certain negative

TABLE 10. **Scale of preference for sub-indicators.**

Preference	Scale
No component	0
Weak	1
Strong	2
Very Strong	3
Excellent	4
Best	5

TABLE 11. **Total assigned value to microgrid configurations for sub-indicators.**

Cases	Land use	Ecosystem balance	Future of technology	Job creation	Comfortable life
Case I	5	5	1	1	3
Case II	19	20	15	13	15
Case III	17	18	13	12	16
Case IV	22	23	18	17	20
Case V	14	15	14	12	12
Case VI	12	13	12	11	13
Case VII	17	18	17	16	17

consequences for the ecology. Due to the intermittent nature of PV and wind, both a battery and a converter must be used at the same time. These technologies have a good future potential in Bangladesh, and it also creates a lot of job opportunities. As a result, the battery has been assigned a value of 5 in terms of job creation. Table 11 presents the sum of the scores of hybrids microgrid configurations from each component. Case VI: PV/Wind/Diesel/Converter/Batter, for example, has the highest score of 23 for ecosystem balance. On other hand, Case I: Diesel only receives the lowest score, with a total point of 1 for both future technology, and employment creation.

X. SUB-INDICATORS NORMALIZATION

The sub-indicators' values are normalized between 0 and 1 so that they can be utilized as input to fuzzy system and to calculate the KSPI's aggregated value on a priority basis. The number 1 and 0 represents best, and worst conditions respectively. Some sub-criterion must be maximized whereas others have to be minimized. The targets relevant to key sustainable performance index with sub-indicators is listed in Table 12. Return on investment, renewable fraction, ecosystem balance, future of technology, job creation, comfortable life must all be maximized, and considered as positive sub-indicators. On the other hand, cost of energy, initial investment, operation and maintenance cost, CO_2 emissions, land use, excess electricity and unmet load is minimized, and presented as negative sub-indicators.

For maximization, the positive sub-indicators normalized value:

$$y_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{28}$$

TABLE 12. **Sub-indicators target for each KSPI.**

Key KSPI	Sub-indicators	Sub-indicator's target
Economy	Cost of energy	Minimize
	Initial cost	Minimize
	Operation and maintenance	Minimize
	Return on investment	Maximize
Environment	CO_2 emissions	Minimize
	Renewable fraction	Maximize
	Land use	Minimize
	Ecosystem balance	Maximize
Technology	Excess electricity	Minimize
	Unmet load	Minimize
	Future of technology	Maximize
Society	Job creation	Maximize
	Comfortable life	Maximize

For minimization, negative sub-indicators normalized value:

$$y_i = 1 - \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{29}$$

Average value of each key sustainable performance indicators:

$$z_i = \frac{\sum_{i=1}^{m} y_i}{m} \tag{30}$$

x = sub-indicators value
x_{min} = minimum value of sub-indicator
x_{max} = maximum value of sub-indicator
y = sub-indicator normalized value
z = average value of each KSPI
m = total number of sub-indicators within KSPI.

Table 13 displays 13 sub-indicators, with values normalized from Tables 9 and 11. This standardization is based on Equations (28) and (29). Case IV has the best energy cost, with a value of 1, and Case VI is the worst scenario with normalized value 0. Table 14 shows the average value of each KSPI calculated from Table 13 using Equation (30). It depicts the economic, environmental, technological, and societal value of each microgrid case. This data will be aggregated by fuzzy logic for KSPI analysis on a priority basis.

XI. FUZZY LOGIC THEORY

Each microgrid topology's score can be calculated using the value of key sustainability performance indicators. The priority score of a hybrid system is evaluated by analyzing economic, environmental, technological, and social aspects.

TABLE 13. Normalized value of sub-indicators.

MG Case	Economy				Environment				Technology			Society	
	Cost of energy	Initial cost	O & M	RoI	CO_2 emissions	Renewable fraction	Land use	Ecosystem balance	Excess electricity	Unmet load	Future of technology	Job creation	Comfortable life
Case I	0.560	1.000	0.000	0.000	0.000	0.000	1.000	0.00	1.000	1.000	0.000	0.000	0.000
Case II	0.792	0.553	0.713	0.677	0.698	0.685	0.176	0.83	0.951	0.511	0.824	0.750	0.706
Case II	0.833	0.706	0.566	0.917	0.587	0.579	0.294	0.72	0.582	0.797	0.706	0.688	0.765
Case IV	1.000	0.572	0.876	1.000	0.863	0.858	0.000	1.00	0.562	0.453	1.000	1.000	1.000
Case V	0.500	0.129	0.938	0.333	1.000	1.000	0.471	0.56	0.568	0.000	0.765	0.688	0.529
Case VI	0.000	0.000	0.620	0.021	1.000	1.000	0.588	0.44	0.000	0.218	0.647	0.625	0.588
Case VII	0.940	0.412	1.000	0.760	1.000	1.000	0.294	0.72	0.621	0.210	0.941	0.938	0.824

TABLE 14. Average value of KSPI.

MG Case	Economic	Environment	Technology	Society
Case I	0.390	0.250	0.667	0.000
Case II	0.684	0.598	0.762	0.728
Case II	0.756	0.546	0.695	0.726
Case IV	0.862	0.680	0.672	1.000
Case V	0.475	0.757	0.444	0.608
Case VI	0.160	0.758	0.288	0.607
Case VII	0.778	0.754	0.591	0.881

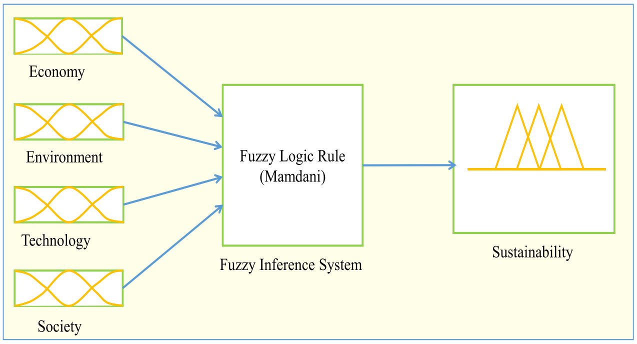


FIGURE 14. Fuzzy-logic controller in MATLAB.

The fuzzy logic Mamdhani type rule, which will be discussed in this section, is used for susatainable microgrid scoring and ranking for Kutubdia Island.

A. FUZZY LOGIC APPLICATION

In 1965, Zadeh suggested the use of fuzzy logic to address the problem of human judgment subjectivity, which is linked to imprecise reasoning in human logic, and to give rationality in decision-making [23]. A fuzzy expert system that combines human knowledge and experience to create linguistic descriptors for variables and fuzzy sets that can be used to regulate the behavior of the problem being investigated. In the MCDA situation, it is critical tools. In the energy sector, authors from all over the world use fuzzy logic as a decision-making tool [22], [29], [34], [36], [59]–[65]. All criteria and their weights must be specified in crisp values, and the rating and ranking of the alternatives must be completed without difficulties. Traditional multi-criteria evaluation approaches may have major practical limitations when used in a real-world decision situation because criteria in the dataset are imprecise or unclear [22]. It is relatively difficult to provide exact numerical values for the criteria and recognition of objects to decision makers due to the availability and uncertainty of information. As a result, most of the selection parameters cannot be presented accurately, and decision makers typically represent the evaluation data of alternative providers' acceptability for various subjective criteria and the weights of the criteria in verbal terms. The following are two key advantages of fuzzy theory in making sustainable microgrid decisions:

- Individual KSPI weights are expressed in linguistic words. As a result, the significance of indicators is explicit for each parameter of microgrid configurations.
- Following the formation of Mamdani rules, the weight is automatically distributed to each KSPI, allowing for self-tuning. As a result, training data is not required to run the system. Also, Kutubdia has no information on Microgrid's case of prior operations.

B. MATLAB FUZZY LOGIC MAMDANI RULES

The Fuzzy Logic Toolbox in MATLAB software allows to easily model Mamdani rules within a fuzzy inference system (FIS). Figure 14 depicts the block diagram of fuzzy processing system. MATLAB uses the average normalized value of the economic, environmental, technological, and social parameters as input parameter. The following is the procedure for determining the comprehensive normalized output of each KSPI using FIS in MATLAB:

Steps-1: The linguistics variable descriptors for economy, environment, technology, society, and sustainability are *Low*, *Equal*, and *High*. Figure 15 shows the triangular membership function (MF) where all KSPI uses the same type of variable with MF. According to principles of fuzzy theory, overlap sets, and a value can be partially belongs to the others set, and have a membership degree. The Equal triangular membership

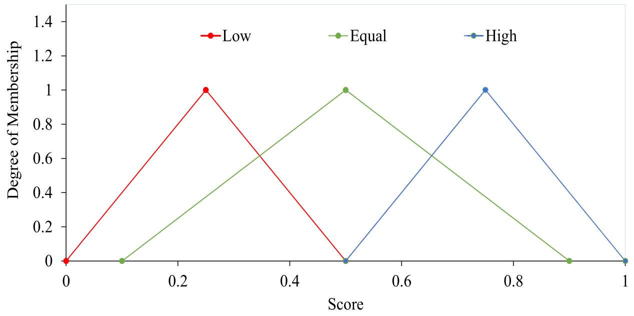


FIGURE 15. Membership function.

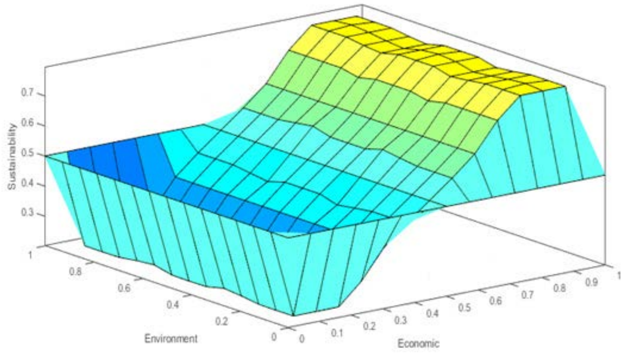


FIGURE 16. Surface of fuzzy rules for economic priority.

function, for4 bexample, is overlapped between *Low* and *High* triangle. The functions intersects indicating 0.6 as the degree of membership.

Step-2: The crisp value is now fuzzified, which assigns the degree of membership to fuzzy sets using a triangular function defined by linguistic variables. The crisp input value has already been normalized to a number between 0 and 1 in this study. As a result, there is no need to scale. The KSPI value can be used directly as an input.

Step-3: The knowledge based rules have now been formulated. *IF-THEN* rules are a Mamdani inference technique. Table 15 mentions how the antecedent and consequent parts are connected in *Mamdhani-FIS*. Logical *AND* is used as fuzzy oprator in the antecedent parts. The total 81 rule is created with economic priority in consideration. The rule 49 for economic preference, for example, will be:

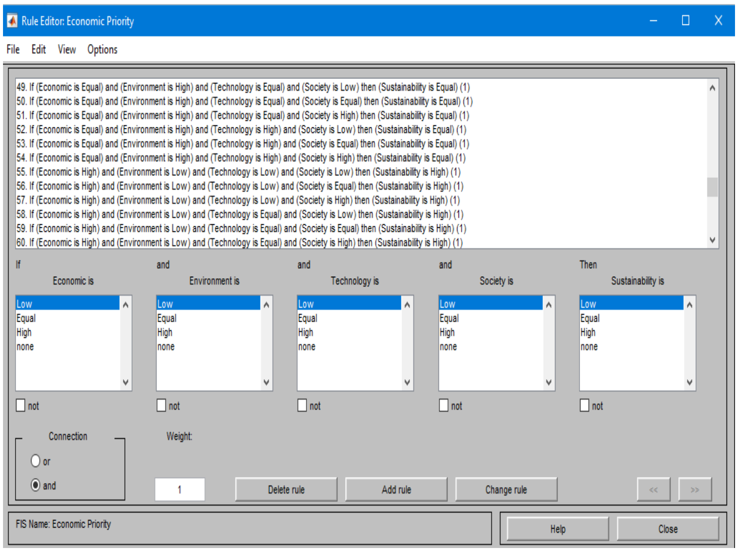
- IF *Economic* is *Equal* AND *Environment* is *High* AND Technology is *Equal* AND *Society* is Low then *Sustainability* is *Equal*.

Environmental priority, technological priority, and societal priority all follow the same set of rules as economic priority. Figure 16 illustrates the surface of a fuzzy rule for environment and economy with sustainability parameters. Figure 17 captures rule for a fuzzy inference system used in the MATLAB simulation.

Step-4: For knowledge base evaluation, fuzzy input is passed through a fuzzy inference system. Using a knowledge base, a fuzzy inference engine can draw conclusions of a system. To convert fuzzy inputs to fuzzy outputs, this procedure utilizes *IF-THEN* logic. The implication method is applied for each rule. The weight of each rule is 1.0.

TABLE 15. Priority basis mamdani antecedent and consequent.

Sl	ANTECEDENTS				CONSEQUENT
	W*	X*	Y*	Z*	S**
1	Low	Low	Low	Low	Low
2	Low	Low	Low	Equal	Low
3	Low	Low	Low	High	Low
4	Low	Low	Equal	Low	Low
5	Low	Low	Equal	Equal	Low
6	Low	Low	Equal	High	Low
7	Low	Low	High	Low	Low
8	Low	Low	High	Equal	Low
9	Low	Low	High	High	Low
10	Low	Equal	Low	Low	Low
11	Low	Equal	Low	Equal	Low
12	Low	Equal	Low	High	Low
13	Low	Equal	Equal	Low	Low
14	Low	Equal	Equal	Equal	Low
15	Low	Equal	Equal	High	Low
16	Low	Equal	High	Low	Low
17	Low	Equal	High	Equal	Low
18	Low	Equal	High	High	Low
19	Low	High	Low	Low	Low
20	Low	High	Low	Equal	Low
21	Low	High	Low	High	Low
22	Low	High	Equal	Low	Low
23	Low	High	Equal	Equal	Low
24	Low	High	Equal	High	Low
25	Low	High	High	Low	Low
26	Low	High	High	Equal	Low
27	Low	High	High	High	Low
28	Equal	Low	Low	Low	Equal
29	Equal	Low	Low	Equal	Equal
30	Equal	Low	Low	High	Equal
31	Equal	Low	Equal	Low	Equal
32	Equal	Low	Equal	Equal	Equal
33	Equal	Low	Equal	High	Equal
34	Equal	Low	High	Low	Equal
35	Equal	Low	High	Equal	Equal
36	Equal	Low	High	High	Equal
37	Equal	Equal	Low	Low	Equal
38	Equal	Equal	Low	Equal	Equal
39	Equal	Equal	Low	High	Equal
40	Equal	Equal	Equal	Low	Equal
41	Equal	Equal	Equal	Equal	Equal
42	Equal	Equal	Equal	High	Equal
43	Equal	Equal	High	Low	Equal
44	Equal	Equal	High	Equal	Equal
45	Equal	Equal	High	High	Equal
46	Equal	High	Low	Low	Equal
47	Equal	High	Low	Equal	Equal
48	Equal	High	Low	High	Equal
49	Equal	High	Equal	Low	Equal
50	Equal	High	Equal	Equal	Equal
51	Equal	High	Equal	High	Equal
52	Equal	High	High	Low	Equal
53	Equal	High	High	Equal	Equal
54	Equal	High	High	High	Equal
55	High	Low	Low	Low	High
56	High	Low	Low	Equal	High
57	High	Low	Low	High	High
58	High	Low	Equal	Low	High



```
49. If (Economic is Equal) and (Environment is High) and (Technology is Equal) and (Society is Low) then (Sustainability is Equal) (1)
50. If (Economic is Equal) and (Environment is High) and (Technology is Equal) and (Society is Equal) then (Sustainability is Equal) (1)
51. If (Economic is Equal) and (Environment is High) and (Technology is Equal) and (Society is High) then (Sustainability is Equal) (1)
52. If (Economic is Equal) and (Environment is High) and (Technology is High) and (Society is Low) then (Sustainability is Equal) (1)
53. If (Economic is Equal) and (Environment is High) and (Technology is High) and (Society is Equal) then (Sustainability is Equal) (1)
54. If (Economic is Equal) and (Environment is High) and (Technology is High) and (Society is High) then (Sustainability is Equal) (1)
55. If (Economic is High) and (Environment is Low) and (Technology is Low) and (Society is Low) then (Sustainability is High) (1)
56. If (Economic is High) and (Environment is Low) and (Technology is Low) and (Society is Equal) then (Sustainability is High) (1)
57. If (Economic is High) and (Environment is Low) and (Technology is Low) and (Society is High) then (Sustainability is High) (1)
58. If (Economic is High) and (Environment is Low) and (Technology is Equal) and (Society is Low) then (Sustainability is High) (1)
59. If (Economic is High) and (Environment is Low) and (Technology is Equal) and (Society is Equal) then (Sustainability is High) (1)
60. If (Economic is High) and (Environment is Low) and (Technology is Equal) and (Society is High) then (Sustainability is High) (1)
```

Connection: ● and
Weight: 1
FIS Name: Economic Priority

FIGURE 17. MATLAB fuzzy logic rules.

TABLE 15. ***(Continued.)*** **Priority basis mamdani antecedent and consequent.**

59	High	Low	Equal	Equal	High
60	High	Low	Equal	High	High
61	High	Low	High	Low	High
62	High	Low	High	Equal	High
63	High	Low	High	High	High
64	High	Equal	Low	Low	High
65	High	Equal	Low	Equal	High
66	High	Equal	Low	High	High
67	High	Equal	Equal	Low	High
68	High	Equal	Equal	Equal	High
69	High	Equal	Equal	High	High
70	High	Equal	High	Low	High
71	High	Equal	High	Equal	High
72	High	Equal	High	High	High
73	High	High	Low	Low	High
74	High	High	Low	Equal	High
75	High	High	Low	High	High
76	High	High	Equal	Low	High
77	High	High	Equal	Equal	High
78	High	High	Equal	High	High
79	High	High	High	Low	High
80	High	High	High	Equal	High
81	High	High	High	High	High

* W, X, Y and Z is KSPI parameters (economy, environment, technology and society). W is specified as high priority parameter, and X, Y, Z is low priority. They form the Antecedent part of the Mamdani rule.
** S denotes the degree of sustainability and forms consequent part of rule.

Step-5: The aggregation method uses maximum procedure to combine all of the executed rules.

Step-6: In the final step, all outputs are defuzzified using centroid technique. The goal of defuzzification is to obtain a crisp output result. As the input data is normalized to a value between 0 and 1, the crisp output data will be within it.

Step-7: All of the scores are now arranged in ascending order. The microgrid configuration with the highest score is chosen as the best.

TABLE 16. **Ranking of microgrid configurations.**

Case	Economic Priority	Environmental Priority	Technological Priority	Social Priority
Case I	6	7	4	7
Case II	4	5	1	4
Case III	2	6	2	3
Case IV	1	4	3	2
Case V	5	2	6	6
Case VI	7	3	7	5
Case VII	3	1	5	1

In summary, the MATLAB-FIS has four inputs, one output, and 81 rules for each KSPI priority.

XII. MICROGRIDS COMPARISON AND RANKING BASED ON FUZZY RULES

Fuzzy logic Mamdani rules are used to evaluate the priority based aggregated score of the sustainable microgrid scenarios. Figure 18 shows comparison of seven different microgrid configurations from Case I to Case VII. Table 16 depicts the ranking process, with the highest score ranked as 1, indicating the best case.

For economic priority evaluation, the total scores achieved by Case I, Case II, Case III, Case IV, Case V, Case VI and Case VII are 0.487, 0.518, 0.528, 0.568, 0.500, 0.457 and 0.527, respectively. Case IV: PV/Wind/Diesel/Converter/Battery microgrid outperforms the other six cases. As a result, it is ranked first and chosen as Kutubdia's first choice. Case III and Case VII have scores that are very close and comparable to one another. Case II, Case V, and Case I are ranked fourth, fifth, and sixth, respectively. Case VI: Wind/Converter/Battery is placed in the last position and receives the lowest score. Because

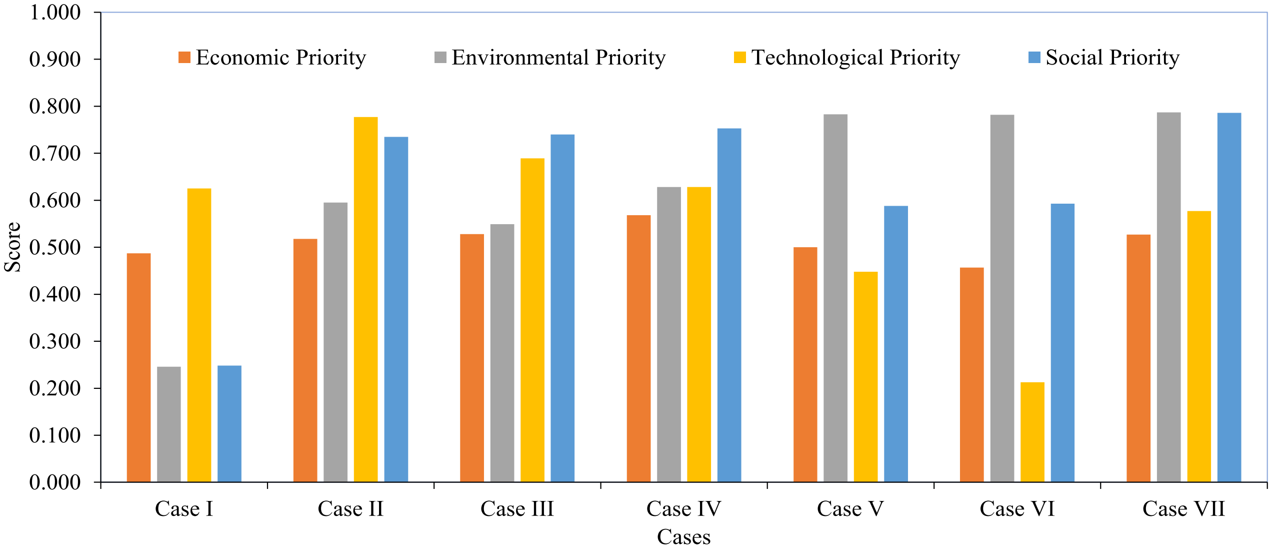


FIGURE 18. **Comparison of sustainable microgrid cases in Kutubdia Island.**

wind turbine generators have a high capital cost and require extensive maintenance cost over the duration of the project's lifetime. The high cost of electricity, despite the fact that it produces no CO_2, will be a burden for the island's population.

When it comes to environmental preferences, emission sub-indicators are given significant weight than other indicators. Case VII: PV/Wind/Converter/Battery hybrid system is the best alternatives. Because PV and wind turbine produce no pollutants, they are considered environmentally beneficial sources of electricity. The combined score of economics, environment, technology, and society is 0.787, putting it in first place. The architectures of PV/Converter/Battery, on the other hand, comes in second, followed by Case VI in third. Case VI obtains a 0.628 score. Case IV, Case II, and Case III, in that order, are the fourth, fifth, and sixth configurations. The standalone diesel engine generator, or Case I, is the worst situation because it emits more CO2 and gets the lowest score of 0.246.

PV/Diesel/Converter/Battery, configuration of Case II, is ordered first when evaluating technological priority of microgrid. With fuzzy rules, the computed score of four KSPI is 0.777. Solar is an emerging technology in Bangladesh that will be widely employed in the future. The government and non-governmental institutions of Bangladesh are hardly working to promote the solar industry or to meet the country's power sector's sustainable development goals. With a score of 0.689, the microgrid of Case III: Wind/Diesel/Converter/Battery is ranked second. Case VI, Case I, Case VII, Case V, and Case VI are the recommended combinations from third to seventh. Due to a shortage of skilled manpower, the wind-battery combination remains an untapped technology. Case VI has a fuzzed score of 0.213 and that is not regarded a suitable configuration.

According to the fuzzy norms, the weight of society is now the most important factor for the Kutubdia Island. PV/Wind/Converter/Battery receives the highest score of 0.786, which is similar to environmental priority. The off-grid system of Case IV: PV/Wind/Diesel/Converter/Battery, on the other hand, has been ranked second highest. As a result, Case III, Case II, Case VI, Case V, and Case I are in sequence from third to seventh. The demand for a standalone diesel generator of Case I is quite low. In facts, diesel generator is not well-liked by the community. Its pollution will have a negative impact on Kutubdia Island's society.

XIII. SUSTAINABLE MG CONFIGURATION ANALYSIS

The economic condition of people of Kutubdia Island is not good. As a result, considering economy as the first priority only Case IV: PV/Wind/Diesel/Converter/Battery microgrid is analyzed in this section.

A. ELECTRICAL ANALYSIS

Figure 19 demonstrates monthly electricity generation from solar panels, wind turbines, and diesel generators. Except in February, November, and December, the total output exceeds 500MWh. Due to the rainy season, solar production is lower in June and July than in other months. Wind output power, on the other hand, is extremely high in comparison. The diesel generator is only used between March and October, and its usage is always quite low throughout the year. Figure 20 displays the percentage of electricity produced by each generator. Wind turbine generators provide the most energy, with 69 percent and 6377223 kWh/year. Solar accounts for 23% of the energy share. The annual power output is 2126614 kWh. Only 8% of the energy is supplied by the diesel generator, which is quite low.

B. FINANCIAL ANALYSIS

The fraction of net present cost (NPC) for each component is shown in Figure 21. The NPC of the project is 17614900.88$.

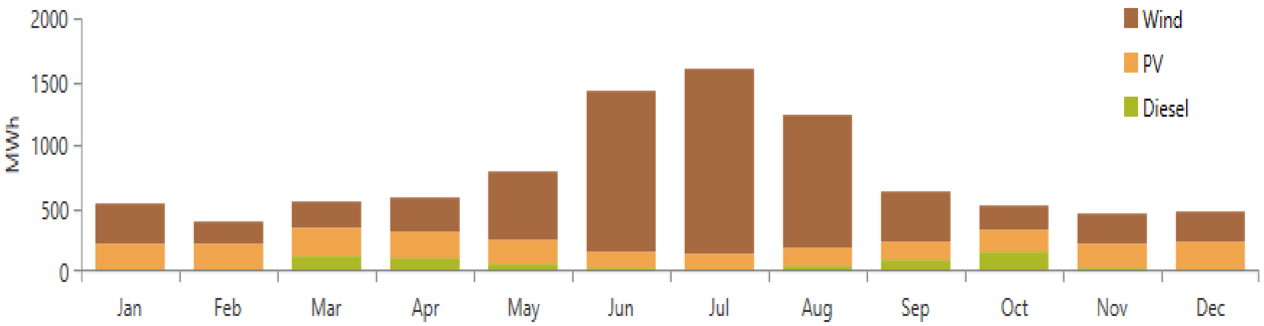


FIGURE 19. Monthly electricity production.

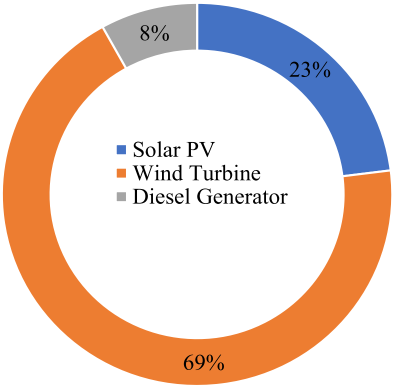


FIGURE 20. Share of energy.

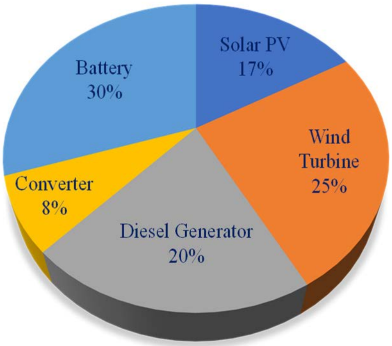


FIGURE 21. Percentage of net present cost.

Solar PV, Wind, Diesel, Converter, and Battery each have a 17 percent, 25 percent, 20 percent, 8%, and 30% share of NPC, respectively. Figure 22 depicts annual discounted cash flows for the project's first 25 years. The most cash go into the beginning of the project. For exceeding output power, the battery is replaced after ten years. Other than solar PV, all other components are replaced during the duration of the project. At the completion of the project's lifecycle, there is a profit. Figure 23 depicts the cost component. The cost of a diesel generator is lower, whereas the cost of a wind turbine is higher. PV and wind turbines do not require any fuel.

TABLE 17. Emission of pollutants.

Pollutant	Emissions (kg/yr)
Carbon dioxide	522,110
Unburned hydrocarbons	143
Carbon monoxide	2,701
Sulfur dioxide	1,276
Nitrogen oxides	518
Particulate matter	23.1

C. EMISSION ANALYSIS

Due to the usage of renewable energy technology, the PV/Wind/Diesel/Converter/Battery microgrid architecture reduces large amounts of CO_2 emissions as well other gases compared to only standalone diesel generator. One of the prerequisites of Bangladesh's sustainable development program is moving toward low-pollution emissions. As a result, it is a more environmentally friendly power generation system than the island's current status. The emission of various gases is mentioned in Table 17.

D. SENSITIVITY ANALYSIS

The sensitivity of energy cost, net present value, and operation and maintenance cost with respect to solar irradiation, wind speed, fuel price, discount rate, and electrical demand is addressed in this section for Case IV which is the best sustainable microgrid configuration for Kutubdia Island when economy is high priority.

Figure 24 indicates the cost of energy sensitivity. If irradiation, wind speed, and electrical load are all increased by 30%, the cost of energy falls. Increasing the price of fuel, and the nominal discount rate up to 130 percent, however, raises the cost of electricity. Wind speed has the sharpest negative slope, while the discount rate has the steepest positive slope, indicating that they are more sensitive to per unit energy cost. When the fuel cost dropped by 70%, the electricity cost also dropped to 0.209$/kWh. The cost of energy for high wind speeds has dropped to 0.187$/kWh.

Figure 25 illustrates the sensitivity of net present cost. With increased irradiation level, wind speed, and nominal discount

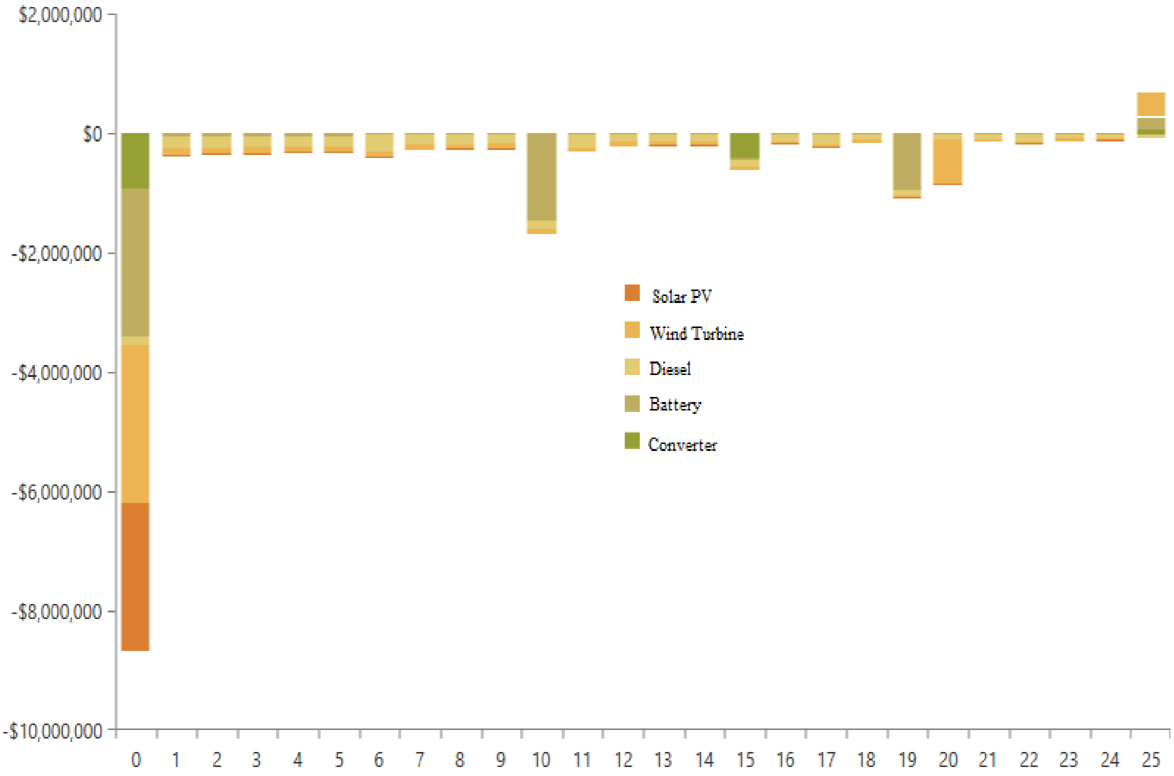


FIGURE 22. Annual discounted cash flow.

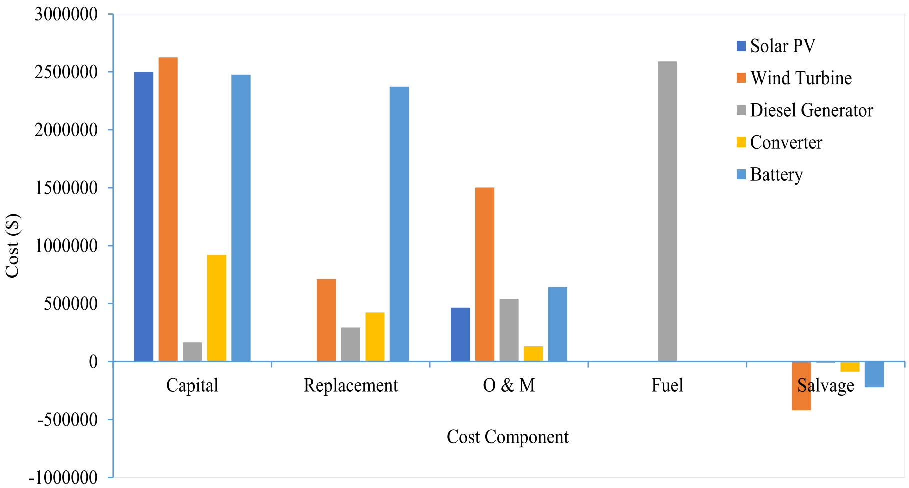


FIGURE 23. Cost component.

rate, the NPC drops. If fuel prices are low and the electric load is reduced to 70%, the NPC would be lower. The NPC is largely affected by the electric load. When the wind speed drops to 3.34 m/s from the base value, the NPC rises to 21 million dollars.

Figure 26 outlines the costs of operation and maintenance. Maintenance costs are reduced with nominal discounts and solar irradiation. Solar PV, on the other hand, has a low operational cost. However, a 30% increase in wind speed reduces large amounts of operational costs, while the electric load follows the opposite trend. The decrement of fuel price follows the path of nominal discount rate. When fuel prices rise to 1.18 $/L, however, O&M cost has increased to 461490 $/year.

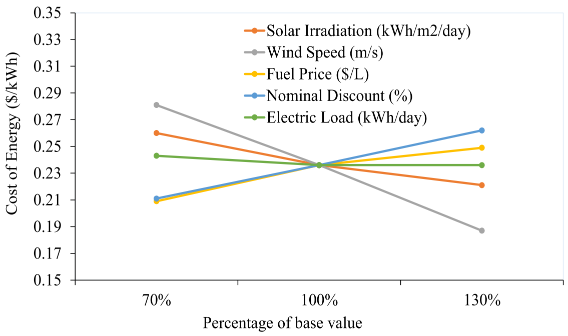


FIGURE 24. Cost of energy sensitivity.

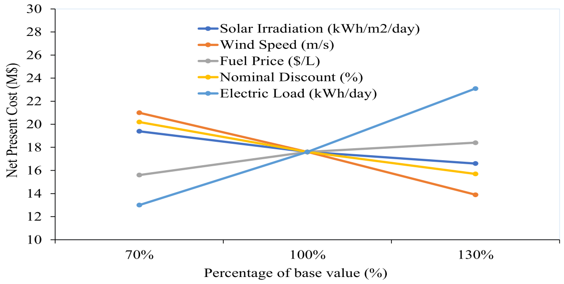


FIGURE 25. NPC sensitivity.

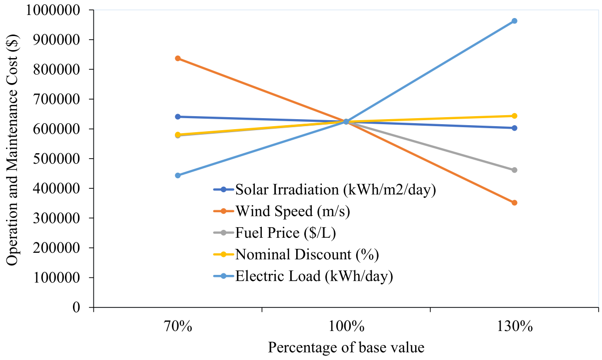


FIGURE 26. Operation and maintenance cost.

XIV. CONCLUSION

A modeling framework for microgrid selection in Kutubdia Island representing key sustainable performance indicators has been proposed. The four KSPI parameters called economy, environment, technology, and society, as well as their 13 sub-indicators are taken into account. The selected sub-criterions were cost of energy, initial cost. operation and maintenance, return on investment, CO_2 emissions, renewable fraction, land requirements, ecosystem balance, excess electricity, unmet load, future of technology, job creation and comfortable life. The HOMER software used as load-following dispatch technique for optimizing seven different configurations. It determined 8 sub-indicators out of total 13 criterion and others 5 sub-indicators were assessed by knowledge base. Finally, the priority basis aggregated score of sustainable microgrids were achieved by Mamdani fuzzy logic rules and provided relative ranking to choose best alternatives. The following major conclusions can be drawn from the microgrid assessments focusing on sustainability strategy in the context of Bangladesh's Kutubdia Island.

- PV/Wind/Diesel/Converter/Battery solution represents best microgrid architecture for economic priorities considering local resources. Due to the low-income level of the community, this configuration can be installed. Such optimal system architecture includes 1250 kW PV arrays, 400 pieces of wind turbines of 10 kW each, a 450-kW diesel generator, 1150 kW converter, and 2250 battery units with 1kWh each.
- When considering both environmental and social factors for microgrid sustainability, the PV/Wind/Converter /Battery system offers attractive option. However, the cost of energy is prohibitively expensive in a low-income area. This type of microgrid is applicable to high-income nations while emitting no carbon dioxide.
- Hybrid PV/Diesel/Converter/Battery alternative becomes feasible considering the technological priority. This is because of the skilled personnel, and technology of PV is available in Bangladesh.
- Priority level of KSPI in a hybrid microgrid system will vary depending on a region's energy resources, policy and identified sustainable indicators. The relative importance and vagueness of criterion can be varied by fuzzy rules.
- The discount rate, wind speed, and load pattern all have significant impact on energy costs, implying that they are the most influential parameters for microgrid project cost.
- Overall, the proposed methodology has demonstrated its strategic performance for remote island. It will also certainly be helpful for academicians and policymakers to identify suitable microgrid configurations especially in any remote location of developing country by emphasizing specific sustainable indicators.

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