International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 2, April 2024, pp. 1334~1351
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i2.pp1334-1351

Feasibility and sustainability analysis of a hybrid microgrid in Bangladesh

Aditta Chowdhury[1], Monirul Islam Miskat[1], Tofael Ahmed[1], Shameem Ahmad[2], Md. Rifat Hazari[2], Lilik Jamilatul Awalin[3], Saad Mekhilef[4]

[1]Department of Electrical and Electronic Engineering, Chittagong University of Engineering and Technology, Chattogram, Bangladesh
[2]Department of Electrical and Electronics Engineering, American International University-Bangladesh, Dhaka, Bangladesh
[3]Department of Electrical Engineering, Faculty of Advanced Technology and Multidiscipline, Airlangga University, Surabaya, Indonesia
[4]School of Science, Computing and Engineering Technologies, Swinburne University of Technology, Melbourne, Australia

Article Info

Article history:

Received Aug 25, 2023
Revised Dec 3, 2023
Accepted Dec 26, 2023

Keywords:

Bangladesh
Hill tracts
Microgrid
Renewable
Sustainable energy

ABSTRACT

The demand for renewable sources-based micro-grid systems is increasing all over the world to address the United Nation's (UN) sustainable development goal 7 (SDG7) "affordable and clean energy". However, without proper viability analysis, these micro-grid systems might lead to economic losses to both customers and investors. Therefore, this paper aims to explore the feasibility and sustainability of a hybrid micro-grid system based on available renewable resources in remote hill tracts region of Bangladesh. Nine different scenarios are analyzed here, and a combination of solar, hydro, biogas, and diesel generator systems are found to be the best feasible solution in regard to the least cost of electricity and emission. The optimized result shows that with a renewable fraction of 0.995, the unit levelized cost of energy of the micro-grid system is $0.182 and it emits 54 and 117 times less CO_2 compared to grid-based and diesel-based systems. Further, the fuel share of the system being 0.5% and greenhouse gas per energy being 0.06425 kg/KWh, validate the system as highly sustainable and eco-friendly. With the ability to fulfill load demands without interrupting supply, and reducing the emissions of greenhouse gases, the designed microgrid can provide sustainable energy solutions to any hill-tracts of Bangladesh.

Corresponding Author:

Lilik Jamilatul Awalin
Department of Electrical Engineering, Faculty of Advanced Technology and Multidiscipline, Airlangga University
Surabaya, Indonesia
Email: lilik.j.a@ftmm.unair.ac.id

1. INTRODUCTION

As the population is increasing and the industrial revolution is happening worldwide, Bangladesh is facing a high energy demand like other developing countries. According to the Bangladesh Government Report 2023, 100% of people have access to electricity but not uninterrupted supply, and the average increase in energy consumption is accelerating at a rate of 6% [1], [2]. According to the Ministry of Power, by 2030, the total power demand will be 34,000 MW [3], [4]. Bangladesh government is trying to meet energy demand by utilizing all resources to ensure affordable electricity for people to meet the United Nation's (UN) sustainable development goal 7 (SDG7), "affordable and clean energy". However, in rural areas, many people are still out of electricity because, due to environmental and economic constraints, grid extension in hilly areas is not viable [5]–[7]. Further, to ensure socio-economic development, sustainable and uninterrupted electricity generation is crucial. Microgrids might solve the problem of off-grid areas if available renewable energy resources can be utilized efficiently and cost-effectively [8]–[11]. Moreover, such a system that depends on renewable energy can release the pressure on fossil fuels and reduce the existing energy scarcity [12], [13].

Over the decades, various research has been conducted by numerous researchers to find out the most feasible solution for electricity problems in remotely connected areas. Mehrpooya *et al.* [14] presented a hybrid system considering economic, technical, and environmental indicators. However, their study did not consider life cycle emissions (LCE), duty factor (DF), and sensitivity analysis of different components cost. In study [15], a techno-economic performance of a battery/hydro/hydrogen storage-based hybrid system is performed for an area in Sharurah, Saudi Arabia. A combination of PV/wind/diesel/pumped hydro systems is the most environmentally friendly system. For urban residential standalone hybrid energy systems of India, a reliable and feasible system configuration is proposed in [16], to fulfill the electrical energy requirement. Wehbe [17] has analyzed the optimization of power generation to meet electricity demand in Lebanon. It is found that there is a great reduction in the cost of electricity generation if fuel oil can be replaced by natural gas for the production of electricity. An off-grid hybrid system based on PV/wind/hydro/diesel generator (DG) is designed in [18], to provide electricity supply to a house close to Seyhan River, Turkey. Ahmad *et al.* [19] performed a feasibility study of a poly-generation microgrid at Aligarh Muslim University (AMU) and found that a PV/Battery system is the most feasible solution for grid mode at AMU. Ahmad *et al.* [20] analyzed the economic and ecological aspects of microgrids for nine different scenarios in India. Khamharnphol *et al.* [21] have designed a hybrid system based on solar, wind, and diesel generator for an island in Thailand called Koh Samui. Their system achieved a levelized cost of electricity of \$0.20/KWh. However, the sensitivity and sustainability of the system are not analyzed. A hybrid system was optimally designed for mixed-use buildings to minimize the net present costs using the HOMER Grid [22]. Belboul *et al.* [23] have designed a hybrid microgrid system consisting of photovoltaics (PV), wind turbine, and diesel generator for 15 residential houses in Djelfa, Algeria. A study led by Ahmed *et al.* [24] was conducted for a Guinea Savannah region, which achieved a renewable fraction (RF) of 70% with a levelized cost of energy (LCOE) of \$0.689/KWh. Eteiba *et al.* [25] designed an optimized off-grid PV/biomass hybrid system in Egypt to minimize the net present cost (NPC). Rajbongshi *et al.* [26] suggested that a hybrid energy system having renewable and conventional fuel is a good solution for rural electrification, especially where grid extension is financially not feasible. A study conducted by Hossain *et al.* [27] found that a stand-alone hybrid renewable energy system has less NPC, LCOE, and greenhouse gas (GHG) emissions than a diesel-only system. It can be seen from the previous discussion that researchers from all over the world are trying to enhance the performance of renewable energy-based hybrid grid systems to utilize cleaner power from renewables.

Nevertheless, many studies have been conducted to find the most economical solution for electricity issues in remote areas in Bangladesh. For instance, Arefin *et al.* [28] proposed a hybrid power generation system based on solar/wind/biomass for the electrification of an island in Bangladesh. A survey was conducted by Chowdhury *et al.* [29] to find the hydro potential of Chotokomoldoho and a hybrid generation system for Kutubdia island with cheap electricity cost and less environmental pollution was developed in [30]. Several feasibility studies have been conducted by different authors to solve the electricity problems in Adorsho Char [31], Saint Martin's Island [32], Nijhum Dip [33], and Sitakunda [34]. However, these studies have several limitations. The authors have not considered onsite data while designing microgrid models. In addition, the sustainability of the designed micro-grid systems has not been discussed. Further, in the above studies, the techno-economic feasibility of off-grid micro-grid for remote villages and islands has been covered. However, the survey of micro-grids for hill tracts is limited, though many people in those locations are deprived of electricity.

From the abovementioned literature reviews, it is pretty evident that microgrid is a viable solution to mitigate the energy crisis. However, sustainability analysis of these designed grid systems has yet to be carried out in these studies. It is very important to analyze the sustainability of the developed system by considering several sustainability indicators like renewable energy share, fuel share in electricity and energy, and Net energy import dependency [35], [36]. Though microgrid technology is relatively mature, policymakers should consider the prospects to harness maximum social, economic, and environmental benefits. While developing a sustainable microgrid, many problems need to be addressed, such as the availability of renewable resources, location geography, difficulty with technology operation, maintenance, and economic concerns [37]. In addition, it is necessary to design the grid system optimally to enhance the performance [38], [39]. Resource data, for example, solar radiation data, biomass resources data, water flow, and wind flow rate data, should be taken for a sufficient period to analyze the availability of energy sources. Otherwise, the developed microgrid fails to produce sufficient energy.

Based on the aforementioned discussion, this research represents the viability analysis of a microgrid system based on the renewable energy resources of a remote hill tract region of Bangladesh to design a feasible model of a microgrid system. The micro-grid model has been analyzed under several sustainability indicators to evaluate the system's sustainability. Renewables, namely solar, wind, hydro, and biomass, are considered for analyzing the various performances of the designed micro-grid system, as they are abundant in the hill tract region of Bangladesh. The techno-economic analysis is carried out based on the best NPC, LCOE, and operating costs to determine the optimal design of the system. The environmental effects associated with micro-grid systems for nine cases are also presented, along with the sensitivity analyses to choose the most economical design over multiple conditions. The HOMER platform is used for modeling, simulation, and techno-economic and environmental evaluations of the microgrid system.

The rest of the paper is designed as follows: section 2 shows the methodology used to develop a feasible micro-grid system. Section 3 represents the research's result and analysis. Finally, a conclusion is drawn in section 4.

2. METHOD

This research aims to explore a sustainable and feasible micro-grid system considering available renewable resources in the remote hill tracts region of Bangladesh. For this reason, a site in a hilly area has been selected where the national grid has no supply. Available renewable resources data are collected throughout the geography of this remotely located site. Then, the data is used to simulate using the HOMER software. Nine different cases have been studied with varying combinations of available resources.

2.1. Site selection

Naraichori, a rural area in Rangamati, was selected in this work for a feasibility study of the hybrid microgrid. Renewable energy resources are available in Naraichori, which are set for modeling the micro-grid system. Naraichori is located in the hill tract region of Chittagong 22.656505°N and 92.120403°E coordinates, where the transportation system is mainly dependent on boats. Google satellite image of the location is shown in Figure 1.

Figure 1. Site location of Naraichori (Source: Google Maps)

2.2. Data collection

On-site data are collected from Naraichori, a remote area in Rangamati, Chattogram. Solar radiation and wind data are collected using a solar pyranometer and anemometer, respectively. The data collection matrices are organized based on the following variables: i) collecting data on the Total No. of people living in the Naraichori locality, ii) counting the total No. of families, iii) collecting overall electrical power demand, iv) collecting the number of livestock like cows, goats, and sheep, v) exploring biomass resources such as Jhum cultivation and other crop residues, vi) measuring solar irradiation using pyranometer, vii) collecting wind speed data using an anemometer, and viii) measuring water flow rate in nearest hydro resource for accessing hydro potential.

2.2.1. Load data collection

About 450-500 people live within about 70 families in Naraichori, and most of the people are associated with agriculture to earn their livelihood. During the day time, they work in the field, due to which the load demand is negligible at that time. For this study, all the locality families are categorized into three groups based on family size, economic condition, and load demand for load calculation.

Load demands for the families in groups 1, 2, and 3 are shown in Table 1. Group 1 includes ten families, which are prominent in the context of family members, and their load demand is high as well. It can be seen from Table 1 that each family of group 1 uses two tube lights, five energy lights, three fans, and three sockets on average. Group 2 includes 25 families which have a moderate number of family members. In addition, Table 1 shows that each family of group 2 uses three energy lights, three fans, and three sockets on average. Group 3 includes 35 families, which is the highest in number among all the groups. These are the families having a lower number of family members or having poor economic conditions. It is seen from Table 1 that each family of group 3 uses two energy lights, one fan, and three sockets on average. A water pump for the entire locality is also considered for the water supply.

Table 1. Load calculation for different groups of families

Group no.	Load equipment	No. of units per family	Rating per Unit (Watt)	Total units of equipment	Total equipment load (Watt)
1	Tube light	2	43	20	860
	Energy light	5	16	50	800
	Fan	3	50	30	1500
	Sockets	4	20	40	800
2	Energy light	3	16	75	1200
	Fan	3	50	75	3750
	Sockets	3	20	75	1500
3	Energy light	2	16	70	1120
	Fan	1	50	35	1750
	Sockets	3	20	105	2100
For the entire locality	Water pump	-----	1000	1	1000

The total energy requirement is depicted in Table 2, where it is found that the kWh calculation is divided into two periods. Summer use of light will not be as much as winter since daylight is available for a longer time. Again, the use of fans will be more in summer than in winter. So, it is assumed that each light is used for 5 hours during summer and 6 hours in winter on average, whereas each fan is used for 12 hours in summer and 2 hours in winter on average. Sockets and accessories are also considered for mobile and battery charging. Total daily kWh demand both in summer and winter is calculated separately. By considering the daily electricity usage hours along with 30% of peak demand in off-peak hours it is found that the total required load in the summer period is 45.461 MWh, and in the winter period, it is 11.632 MWh. Also, the load requirement for the water pump is 638 kWh throughout the year.

Table 2. Total energy requirement

Load type	Total load (Watt)	Daily hour usage in summer (March-October)	Total daily watt-hour in summer (March-October)	Daily hour usage in winter (November-February)	Total watt-hour in winter (November-February)
Tube light	860	5	4,300	6	5,160
Energy light	3,120	5	15,600	6	18,720
Fan	7,000	12	96,000	2	14,000
Socket	4,400	3	13,200	3	13,200
Total		--	129,100	--	51,080

2.2.2. Software selection

HOMER was developed under the U.S. Department of Energy at the National Renewable Energy Laboratory (NREL) [40] which is used in this study. Renewable energy systems are considered to avail energy at a reasonable price ensuring energy independence [41]. HOMER is very handy for analyzing, evaluating and checking models for both grid-connected and standalone systems. HOMER considers all the data with constraints, and using algorithms, it determines the most optimum solution. Taking the technological considerations into account, HOMER performs sensitivity and optimization analysis, which resulted in the cost and feasibility of the considered models. HOMER also can determine the life cycle cost, LCOE, the net present cost of electricity (NPC), carbon emission, RF, greenhouse gas (GHG), and depreciation cost. It is required to give input of hourly load, the solar radiation data, wind and hydro flow data, and amount of biomass. in HOMER, and the simulation is done next to analyze the performance of the designed microgrid. So, appropriate load and resource data need to be collected first.

2.2.3. System components

The proposed model for designing the microgrid system is shown in Figure 2. The system consists of a PV module, diesel generator, biogas generator, hydro, battery, and converter. The investment cost, operation, and maintenance (O/M) cost and replacement cost are selected according to [42] and provided in the HOMER. The investment, O/M, and replacement cost are $1300/kW, $20, and 0 respectively with an expected lifetime of 25 years. For the diesel generator, they are $370/KW, $0.05/h, and $296/kW respectively while the biogas generator requires $400/kW capital, $0.1/h O/M, and $300/kW replacement cost. The water pump needs a cost of $4000 as capital cost and $100/year for O/M with $3000 replacement cost. Battery costs about $1100 for investment and $1000 for replacement. Converter requires $800 for capital, $750 for replacement, and $8 for maintenance. The lifetime for the battery and converter is selected as 12 and 15 respectively while for the diesel generator, biogas generator, and hydro pump it is 20 years.

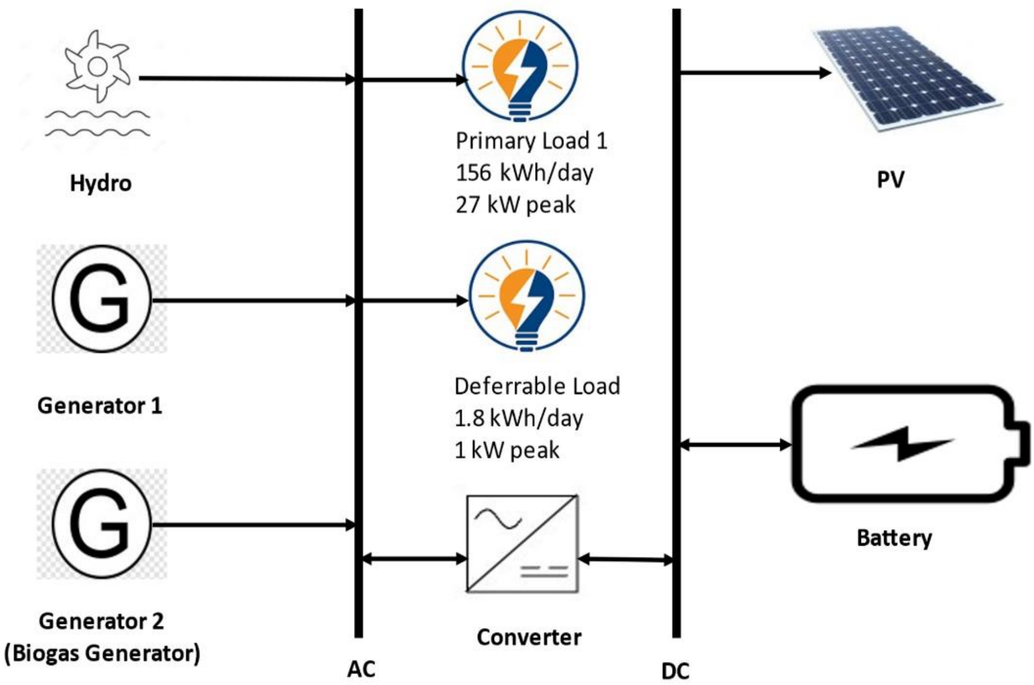

Figure 2. Proposed hybrid micro-grid system

2.2.4. Hourly load calculation

The hourly load data are taken considering some assumptions. Considering the lights are in use for 6 hours daily from 6 pm to 12 pm in the whole year. The fans are in use for about 14 hours daily on average during the summer period. Also, two-pin sockets and other accessories are used for three hours on average. The daily load profile of a whole year is shown in Figure 3. It indicates that the electrical load demand is higher in the summer season. As almost all are busy in agricultural activities during the daytime the load demand is negligible in that period. So, 30% of peak demand is considered in that period. The load demand is higher at night, especially in summer. The seasonal load profile is shown in Figure 4. It represents the average of the daily maximum of all the days in the month. It can be seen that load demand is comparatively high during summer, from March to October, and low in the winter period, from November to February.

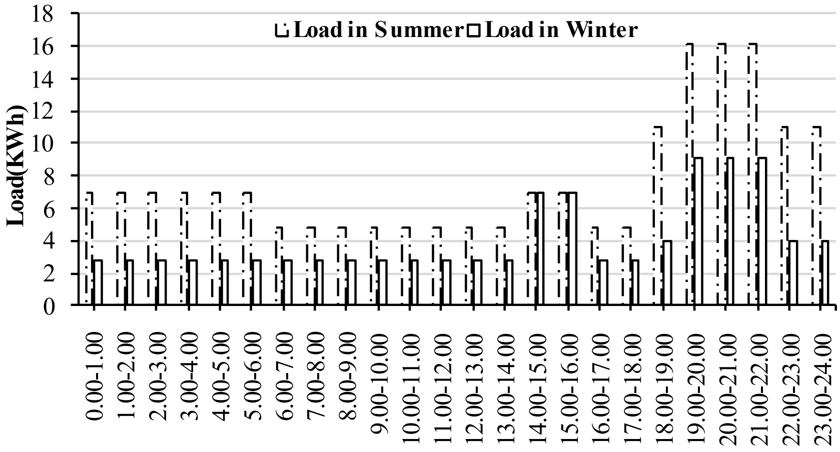

Figure 3. Daily load profile over the year

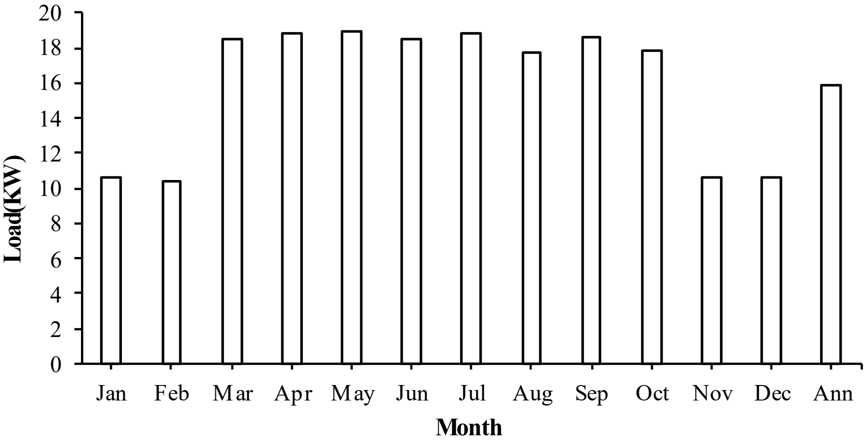

Figure 4. Seasonal profile of load

2.2.5. Solar radiation data

Solar energy is the most available renewable energy resource and the world has a solar energy potential of about 23,000 TW [43]. NASA Surface Meteorology and Solar Energy database is used for monthly Solar Direct Normal Irradiance (DNI) [44]. These data are taken by HOMER to determine the solar energy that can be produced from the sun's radiation falling on the surface of the location considered. It considers data on average global irradiation level on a horizontal plane with data of total hours in years, which is 8,760 hours. The latitude and longitude of the location are given as input, and the global DNI and clearness index of each month are found. HOMER utilized these data to generate hour-to-hour or day-to-day solar irradiance variability. HOMER represents the solar irradiation data and clearness index in the same plot, and it is easy to understand the variation of global solar irradiance and clearness index over different months. It is important to compare the online data with the practical solar data of the selected site. For this reason, the selected area has been visited several times, and a pyranometer has been used to measure solar DNI data for different days of the year.

Utilizing the HOMER software, available solar data has been tracked. The clearness index, along with solar radiation data, is depicted in Figure 5. From Figure 5, it can be seen that the clearness index is high during December and January. It is found that radiation is maximum during May and minimum in July for the studied locality. Scaled data daily profiles of different months are shown in Figure 6. It is evident from Figure 6 that the month of March, April, and May when it is summer in Bangladesh, has the highest available solar profile. Onsite solar radiation data are collected for this study for four typical days - 25th January, 26th January, 6th March, and 7th March in the year 2022, as shown in Figure 7. It is found that solar radiation is highest from 12.00 pm to 1.00 pm and then gradually decreases.

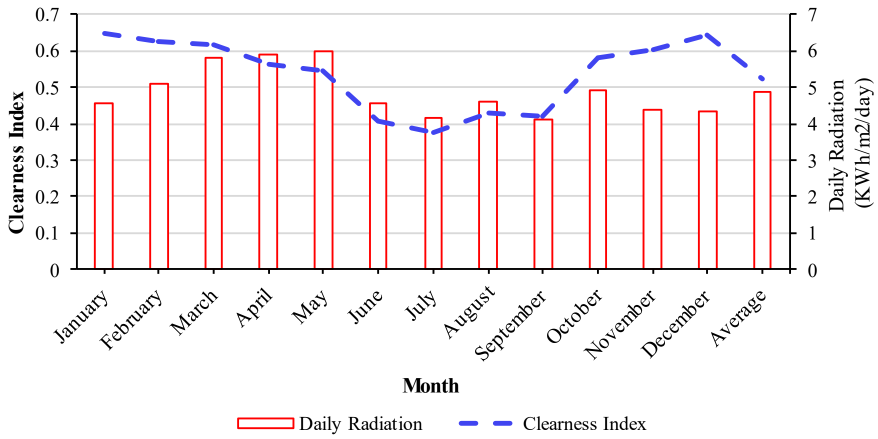

Figure 5. Daily global horizontal radiation as well as clearness index

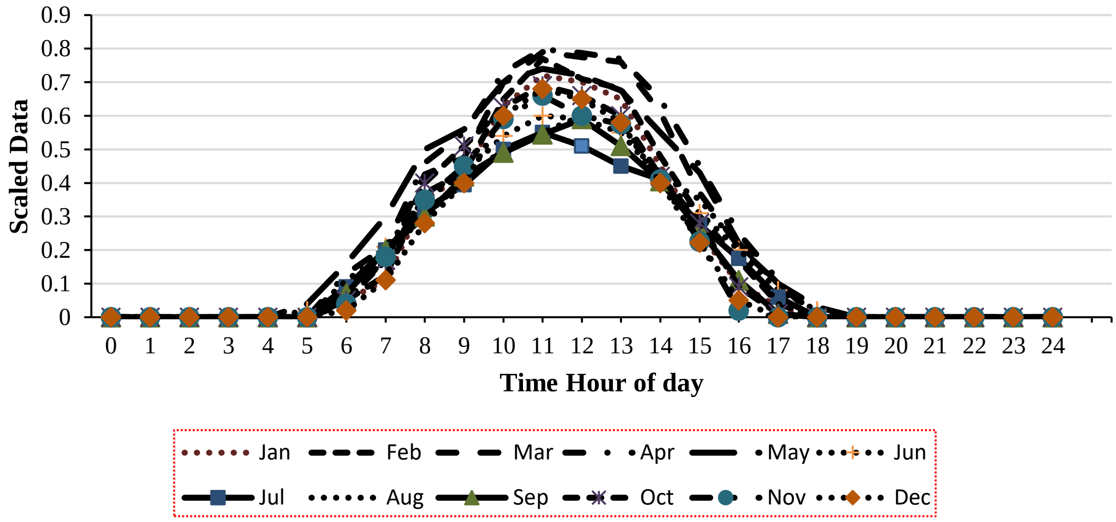

Figure 6. Scaled data of daily profiles of different months

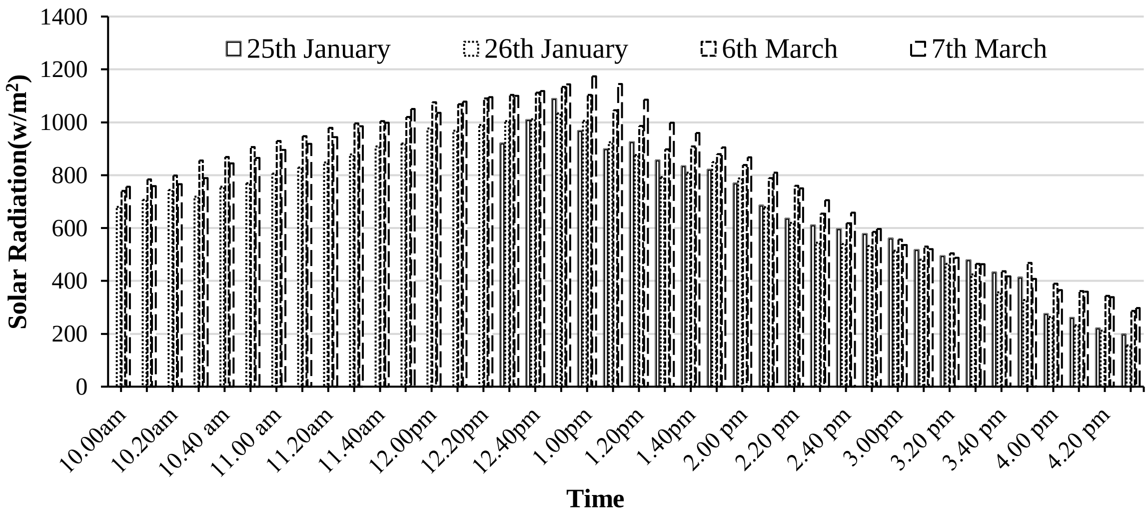

Figure 7. Measured onsite solar radiation data

2.2.6. Wind flow data

A digital anemometer has been used whose model is AM-4200 for data collection. Data has been taken at a hub height of 50m using an anemometer. Data has been collected on four typical days 25th January, 26th January, 6th March, and 7th March of 2022. Average wind speed data for these days are shown in Figure 8. It is evident from the data that the average wind speed on different days varies day to day and this is also not very high to extract electrical energy from this source. An average 6 m/s wind velocity is required to run wind turbine for generating power [45]. It is unavailable at Naraichori from the collected data. Hence, it can be said that electricity generation from wind is not feasible here. Based on this, wind is not considered for this study.

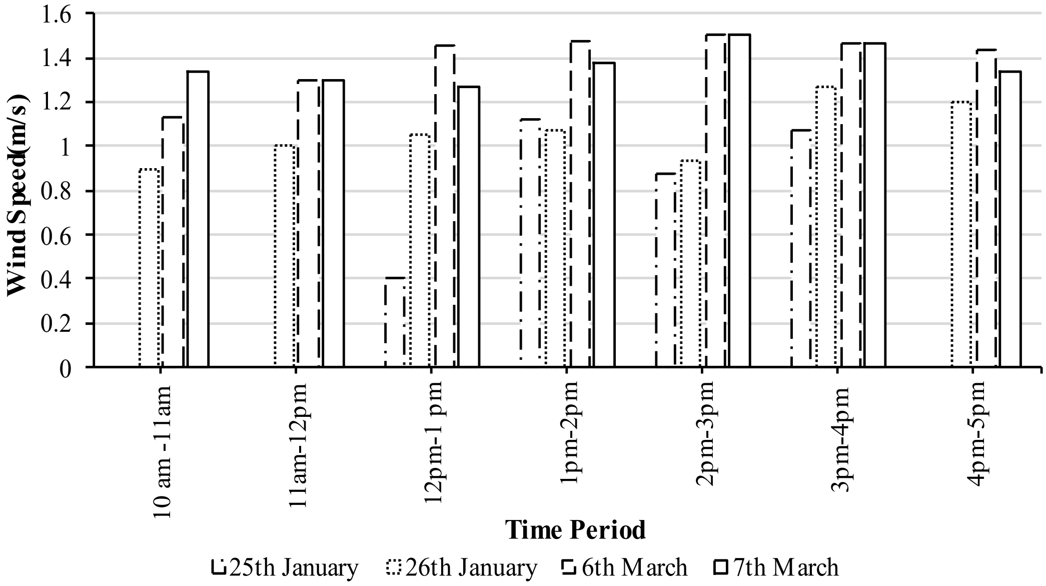

Figure 8. Average wind speed

2.2.7. Biomass data

As a hill tract region, Naraichori is enriched with biomass potential due to the presence of cows and goats in the locality. Data has been collected from different families to find the total number of livestock. Another resource of biomass in this area is the residues of farming, which are potential bioenergy resources. Upon visiting the site, eight cows, around 50 goats, and sheep, as well as 100 chickens or ducks were found. The waste disposal rate can be found in Table 3.

$$Total\ manure\ produced\ per\ day = (8 * 11.5) + (1.5 * 50) + (0.18 * 100)kg = 185\ kg$$
$$= 0.185\ Tons$$

Table 3. Waste Disposal rate of livestock [46]

Livestock	Waste disposal rate/head/Day (kg) (source)	Gas production rate (m^3/kg) (source)	Population	Amount of gas production (m^3)
Cattle	11.5	0.03	8	2.76
Goat and sheep	1.5	0.04	50	3
Poultry	0.18	0.06	100	1.08
Total				6.84 m^3/day

2.2.8. Hydro data

The amount of total power generated depends upon the flow rate of water, gravitational acceleration, and the head of the water stream. The value of this parameter is needed to calculate the power generated from the steam of water. Generated power is the product of these parameters, which is shown in (1) [29].

$$P = \eta * H * Q * g * \rho \quad (1)$$

where H is Gross head in meter, η is efficiency of hydropower plant as a rule of thumb, it is assumed 50% considering all losses [47], Q is Flow rate in m^3/s, g is gravitational constant (9.8 m/s^2), and ρ is density of water=1000 kg/m^3.

The nearest Duppani waterfall in Naraichori has been visited to determine the hydro potential, and surveys have been made on different days throughout the year. Hydro data of Duppani waterfall, Naraichori, measured in June, are shown in Table 4. It is seen from Table 4 that the bucket took 3.235 s on average to fill up on several trials. Considering 50% efficiency, output power is determined using (1).

Table 4. Measured hydro data of Dhuppani waterfall

Avg. Time (s)	Flow rate (L/s)	Actual Flow (m3/s)	Head (m)	Actual Head considering 10% head loss (m)	Considered overall efficiency (η) (%)	Output power (kW)
3.235	6.18	0.00513	45.71	41.14	50	1.035

Output power for other months is calculated similarly over the year. The available water resources in different months and corresponding output power are shown in Figure 9. which shows that the highest water availability is in July and the lowest in December and January.

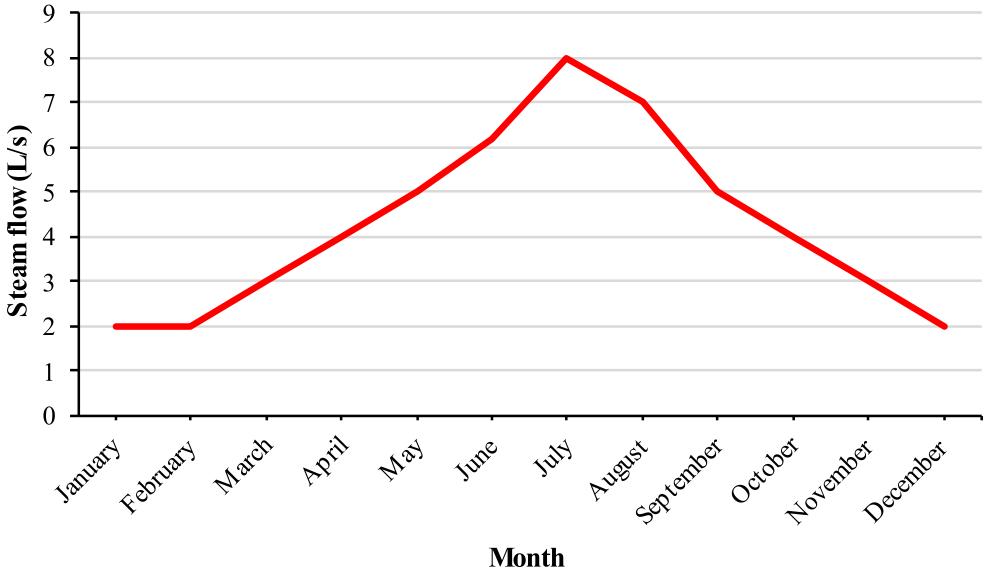

Figure 9. Available water resources over the year

2.3. Designing the optimized model of the hybrid microgrid system

In this study, three indicators: i) economic feasibility, ii) environmental impact, and ii) sustainability indicators are chosen for finding the optimized hybrid micro-grid system for Naraichori, Rangamati. Economic feasibility is a type of cost-benefit analysis which determines if the project can actually be carried out. Environmental impact analysis determines the emissions from the project to give an idea about the impact of it on nature. Again, metrics known as sustainability indicators indicate how sustainable a certain procedure or project is. These will help to analyze the feasibility of the designed microgrid from both financial and environmental perspective.

2.3.1. Economic analysis

HOMER software performs economic analysis also to find out the optimum result. The net present cost denotes the summation of initial capital cost, operation, replacement cost, maintenance costs, and energy costs like fuel costs over its lifecycle project [42]. NPC can be found using (2).

$$NPC = \frac{Ac}{CRF(i,n)} \tag{2}$$

$$CRF(i,n) = \frac{i\times(1+i)^n}{(1+i)^n-1} \quad (3)$$

$$i = \frac{j-f}{1+f} \quad (4)$$

where, *Ac* represents the total annualized cost ($/year), *i* (%) is the annual real interest rate, *j* (%) is the nominal interest rate, *CRF* is the capital recovery factor, *f* (%) is the annual inflation rate and *n* is the project lifetime in a year. Equation (5) helps to measure total annualized cost. LCOE is a crucial factor in hybrid microgrids which can be found using (6).

$$Ac = Ac_{capital} + Ac_{replacement} + Ac_{op_{main}} \quad (5)$$

$$COE = \frac{Ac}{Es} \quad (6)$$

where, the capital cost is $Ac_{capital}$, annualized replacement cost is $Ac_{replacement}$, annualized operation, and Maintenance cost is Ac_{opmain}, and E_S is the energy served in a year.

2.3.2. Environmental impact

Life cycle emissions (LCE) analysis is deployed to find out the emissions from the hybrid system. Equation (7) quantifies life cycle emissions.

$$LCE = \sum_{i=1}^{x} Bi \times El \quad (7)$$

where El denotes energy generated reserved in each unit or component, *x* denotes the number of components utilized in the system Bi (kg CO_2-eq/kWh) denotes the lifetime CO_2 emissions.

2.3.3. Sustainability indicators

Sustainable development is not only about flourishing economically but also environmentally. Sustainability indicators are taken from [48] which are described in the following.

- Share of households (or population) without electricity: This indicator is calculated by dividing the share of households without electricity or electrical energy by the share of households for which dependence on non-commercial fuel exceeds 75% of total use.
- Fuel shares in energy and electricity: Fuel shares in energy and electricity are defined as the production or consumption of specific energy fuels to overall energy usage or production.
- Non-carbon energy share in energy and electricity: Portions of non-carbon energy sources in primary energy sources are defined as non-carbon energy share in energy and electricity.
- Renewable energy share in energy and electricity: It is delineated as the contribution of renewable energy to total primary energy supply, electricity generating capacity and total final consumption. This indicator is measured by determining the ratio of the consumption and production of renewables to the total final energy supply and production.
- Net energy import dependency: This is such a type of sustainability indicator, which is defined as the ratio of net import energy and total primary energy supply (TPES) in a given year. It also indicates how much a country depends on energy imports.
- Greenhouse gas emission from energy production and use per capita and per capita GDP: It is defined as GHG emissions from any process divided by energy produced.
- Resources-to-production ratio: Availability of energy supplies is a key indicator of sustainability. The resources-to-production ratio is the ratio of resources available at the end of a year to the production of overall energy in that particular year.

3. RESULTS AND DISCUSSION

3.1. Case study analysis

Based on the available resources, different combinations of micro-grid systems have been simulated using HOMER software, and the results of each case are analyzed in this section. The different costs included in the various case studies are capital cost, operational cost and net present cost. These costs vary according to the nature of components and size or amount of those selected components used in different cases. Summary of the cases studied are shown in Table 5 and Table 6.

Table 5. Different costs associated with the studied cases

Cases	Capital Cost ($)	Operational Cost ($/year)	Net Present Cost ($)	COE ($/KWh)
Case I	98260	2767	133634	0.182
Case II	101420	2891	138378	0.188
Case III	99740	3120	139621	0.190
Case IV	109740	3049	148721	0.202
Case V	113180	2897	150217	0.204
Case VI	104890	3857	154195	0.210
Case VII	119360	3242	160805	0.219
Case VIII	15160	27184	362661	0.493
Case IX	16890	27995	374759	0.509

Table 6. Different components associated with the studied cases

Cases	Diesel Generator (KW)	Biogas Generator (KW)	PV (KW)	Hydro (kW)	Number of Battery	Converter (kW)
Case I	2	6	52	1.04	99	29
Case II	---	---	53	1.04	122	28
Case III	6	----	53	1.04	104	29
Case IV	2	7	60	---	120	30
Case V	---	5	64	---	119	30
Case VI	7	---	57		120	30
Case VII	---	---	67	---	139	28
Case VIII	8	1	---	1.04	30	20
Case IX	9	---	---	1.04	38	20

3.1.1. Case I: PV/Battery/DG/biogas generator/hydro hybrid system

Among different case studies, the first case system considered is the PV/Battery/Diesel generator/Biogas generator/Hydro hybrid system. This system is the most economical, having the lowest LCOE of $0.182/KWh and an NPC of $133,634. This System includes a 52 kW PV module, 1.04 kW hydro, 2 kW diesel Generator, 6 kW biogas generator, 99 batteries, and 29 kW inverters. The capital cost is the fourth lowest, and the operational cost is the fifth lowest among all the systems considered. The total electrical Power Generated in this case system is 96,925 kWh, with the top contribution from PV, which is 93% and 6% from hydro, 0.5% from biomass, and 0.5% from diesel. Excess electricity is 29,674 kWh, which is about 30.6% of total energy production. So, this system can fully satisfy the load demand of the studied area. In summary, the PV /Battery/DG/Biogas Generator/hydro-based microgrid has the lowest LCOE and NPC among all other systems. Also, this hybrid system releases less amounts of CO_2 and other pollutant gases in the environment compared to other systems.

3.1.2. Case II: PV/battery/hydro hybrid system

This is another case analyzed for the feasibility study. This system consists of a 53 kW PV module, 1.04 kW hydro, 122 batteries, and 28 kW converters. LCOE is $0.188/kWh, which is the second lowest among all the cases. The NPC is $138,378, which is also the second lowest among all the systems. Capital Cost is $101,420, the fifth highest, and the operational cost is $2,891, which is the second lowest. It emits no pollutants in the environment, which is one of the prospective sides of this case.

3.1.3. Case III: PV/battery/DG/hydro hybrid system

This configuration consists of 53 kW PV modules, 1.04 kW of hydro and 6 kW diesel generators, 104 batteries, and 29 kW inverters. The LCOE is $0.190/kWh, which is 4.39% higher than the PV/Battery/Diesel generator/Biogas generator/Hydro hybrid system. The NPC is $139,621, which is 4.48% higher compared to the previous system. The operational cost and capital costs are $3,120 and $99,740, respectively, which are the fifth lowest and fourth lowest among all the considered systems. The maximum contribution is from the PV module of about 93% and rest from diesel and hydro. The system has 31.6% excess energy of total production, which indicates it can satisfy full load demand. The CO_2 emission is 1,678 kg/yr, which is higher but not by a great margin than the PV/Battery/DG/Biogas/Hydro hybrid system. Therefore, it can be said that this system is quite the same as Case I, both economically and environmentally. But a fraction of higher LCOE and NPC along with CO_2 emission make this system less attractive than the first case.

3.1.4. Case IV: PV /battery/DG/ biogas generator hybrid system

This system consists of 60 kW PV, 2 kW diesel generator, 7 kW biogas generator, 120 batteries, and 30kW converters. This is the fourth most economically feasible system among all other systems considered for this case study. The LCOE is $0.202 which is 10.98% higher than the most feasible one. The NPC, in this case, is $148,721 which is 11.28% higher than the PV/Battery/DG/Biogas generator/Hydro based hybrid system. The capital cost is $109,740 the third highest among the discussed systems and also the operating cost is $3,049 which is lower than the previous system analyzed. The total electricity generation is 104,939 kWh of which PV contributes the most (99%) and the excess electricity is 35% in this case. The emission of CO_2 is 564 kg/year which is quite lower than other cases involving diesel generators. It can be said that this system offers a better environmental effect than the most economically feasible case but has higher LCOE and NPC.

3.1.5. Case V: PV/battery/DG/ biogas generator hybrid system

This analysis finds PV/Battery/Biogas generator-based hybrid system is the fifth economically feasible system. This system includes a 64 kW PV module, a 5 kW biogas generator, and 119 batteries. The LCOE is $0.204 which is 12.08% higher than the most economically feasible PV/Battery/DG/Biogas generator/Hydro based hybrid system. The NPC, in this case, is $150,217 which is 12.4% higher than PV/Battery/DG/Biogas generator/Hydro based system. Although the capital cost is the second highest, $113,180 due to a huge number of batteries and a large PV module requirement, the operational cost is the third lowest among all the studied cases being $2,897. Total electricity generation from this system is 111,413 kWh, and 99% is contributed from PV modules. The CO_2 emission is 6.88 kg/yr which is very negligible compared to other systems previously discussed. Though the emission is negligible, however, the higher LCOE and NPC make it an unattractive system.

3.1.6. Case VI: PV /battery/diesel generator hybrid system

In this case, the performance of the PV/DG/Battery system which has a 57 kW PV module, 7 kW diesel generator, 120 batteries, and 30 kW converters, is analyzed. This system has an LCOE of $0.210, which is the sixth highest among the cases. The NPC is $154,195, and the capital cost is $104,890, being the fourth highest. Operation cost is $3,857, also the third highest among the studied cases. The electricity production of this system is 102,429 kWh, with the maximum contribution from the PV module. The emission of CO_2 is 3,131 kg/yr, which is the highest among the discussed systems so far. Therefore, this system has a worse environmental effect as well as a slightly higher LCOE, which makes it less feasible.

3.1.7. Case VII: PV/battery hybrid system

This is a case where only solar is used as a source of energy. It consists of 67 kW PV modules, 139 batteries, and 28kW converters. LCOE is $0.219, while NPC is $160,805 in this system. This system requires the highest amount of PV modules. The capital cost, being $119,360, is the highest among all the systems, and its operational cost is $3,242, which is the fifth lowest among all the cases. Also, this system has no emission of harmful gases in the environment. However, a larger number of batteries and PV modules will make it infeasible because of the higher space requirement for installations.

3.1.8. Case VIII: battery/DG/ biogas generator/ hydro hybrid system

Solar energy is not considered for this case, and the system consists of a 1.04 kW hydro turbine, 1 kW biogas generator, 8 kW diesel generator, 30 batteries, and 20 kW converters. LCOE for this case is $0.493, and NPC is $362,661, which is more than double that of the PV/Battery/DG/Biogas generator/Hydro based hybrid system. The capital cost is $15,160, which is the lowest among all the cases. However, the operation cost is $27,184, being the second highest due to huge fuel requirements. Also, the emission of CO_2 is 75,557 kg/yr for this case, and this is very high compared to the emission of other systems. Huge generation costs and adverse environmental effects make this an undesirable system.

3.1.9. Case IX: DG/hydro hybrid system

The final analysis of the feasibility study consists of a 1.04 kW hydro turbine, 38 batteries, 9 kW DG, and 20 kW converter. The cost of electricity is $0.509, making this the most economically unfeasible system. The NPC is $374,759, which is also the highest and the capital cost is $16,890, being the second lowest, but the operational cost is $27,995, which is the highest. This is neither economical nor environment-friendly, emitting 78,824 Kg of CO_2 per year. So, after analyzing all the case studies, it is observed that Case I provides electricity at a lower cost than other cases. Also, the carbon emission is at a moderate level in this case. So, further results are provided based on this Case.

3.2. Sensitivity analysis

Sensitivity analysis is carried out to get a clear understanding of how the system responds to the changes in the input parameter. For sensitivity analysis purposes, the most optimal case, namely Case I, is considered. Input parameters like capital, PV array, battery, and generator costs have been varied to get an outlook of the variation in LCOE. Figure 10 shows the variation of LCOE concerning the change in the input parameter prices. It can be seen from Figure 10 that LCOE varies most in the case of capital cost variation. If capital cost is reduced by 20%, then LCOE is reduced to $0.155/kWh from $0.182/kWh, which is around a 15% decrease in LCOE. In addition, Figure 10 also shows that if the PV array cost is decreased by 30%, then LCOE decreases by $0.028 per kWh of electricity. In contrast, a 20% increase in PV array gives rise to a 9.8% increase in LCOE than the baseline LCOE. Further, a 20% decrease and increase in battery price lead to a 3.2% reduction and 3.2% increment, respectively, in LCOE measuring from baseline LCOE. Finally, it can be depicted from Figure 10 that converter, DG, and biogas generator costs have a very negligible effect on the variation of LCOE.

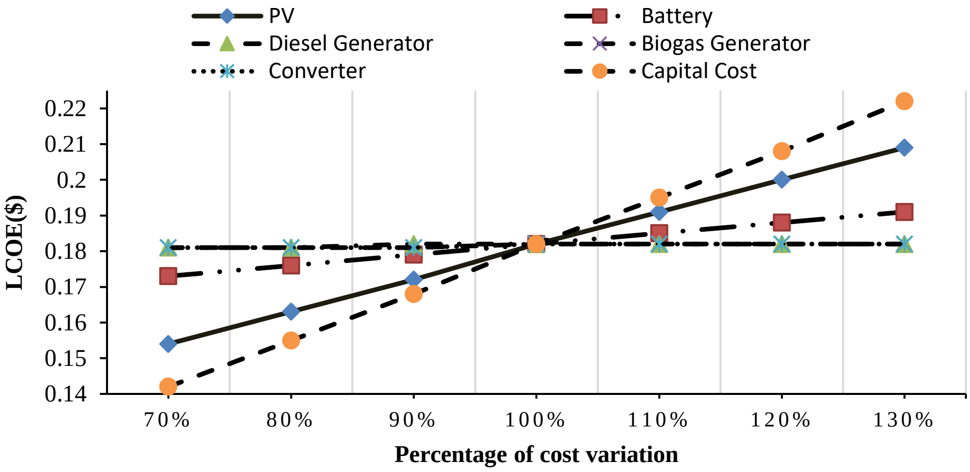

Figure 10. COE variation with the variation of input parameters prices

3.3. Environmental benefits

Environmental benefits consider mainly how much pollutants are released by the system. The principal malefactors for environmental pollution are CO_2, CO, SO_2, and unburned hydrocarbons. The proposed method produces 760 Kg CO_2 per year, ten times less than grid-emitted CO_2. Diesel-based systems emit 89,338 kg CO_2/year, which is around 117 times greater than the emission of the optimal strategy. CO_2 emission (kg/yr) for different methods is shown in Table 7 [42]. This optimal system has an RF of 99.5%, which ensures less emission than other fossil-based plants. Apart from the emission, this system will play a vital role in reducing the deforestation rate in hill tracts.

Table 7. CO_2 emission (Kg/Yr) for different systems [42]

System	CO_2 Emission (Kg/yr)
National grid	41,085
Diesel only	89,338
Kerosene	36,135
Designed optimal system	760

3.4. Sustainability analysis outcomes

Sustainability is a significant concern when considering this kind of hybrid system. Since in Naraichori, there is no grid connection, the share of households without electricity is 100%. The prime goal of this study is to fulfill the 100% load demand of people living in the selected region while considering environmental effects. Almost all people are using non-conventional energy sources for their daily energy needs. So, the share of households without electricity is nearly 1. The proposed system aimed at providing complete load demand for the people in this locality so that they do not have to depend on non-conventional electricity sources, making the system highly sustainable. An optimized system like this can ensure the total load demand of people and decrease dependency on non-conventional fossil fuel resources.

For a highly sustainable system, it is desired that the system's fuel share must be the lowest and the share of non-carbon energy should be the highest. In the case of the proposed method, non-carbon energy share is from PV, hydro, and biomass is (93%+6%+0.5)=99.5%. That means the proposed system will produce less carbon dioxide in its lifetime while producing power. The other 0.5% is from the diesel generator. So, the fuel share of this proposed optimized system is 0.5%, and the percentage of non-carbon energy is 99.5%, which indicates the characteristics of a highly sustainable system. As fossil fuel is depleting at an alarming rate, policymakers must design systems with a higher portion of renewable energy share. Only 0.5% of the system's energy comes from the non-renewable energy source, diesel. As a result, net energy import dependency is as low as 0.5%. As 286 L diesel is needed per year for this system, net energy import dependency is relatively low. Further, this system will show greater sustainability as it does not have to depend on import policy much.

The global warming potential (GWP) was taken from [49], [50], which is shown in Table 8. From Table 5, it is found that the total Global warming potential for the proposed system is 6228.1. From the optimized system, it is seen that the energy produced per year is 96,925 kWh. Therefore, GHG emission for the proposed method is (6228.176/96925)=0.06425 kg/KWh, which indicates less GHG emissions.

The GHG production per energy of 0.06425 kg/KWh indicates less GHG emission potential, which is highly desirable in an eco-friendly hybrid system. Deforestation is high in hill tracts compared with other areas in Bangladesh [51]. Hill tract people cut wood and trees to fulfill their energy demands. The proposed system will ensure their energy demand, and people could utilize wood and biomass residues, which will contribute to decreasing deforestation. One of the crucial advantages of the proposed microgrid is that resources are available, and they will not run off soon like fossil fuels. This optimized system utilizes renewable energy resources for power generation, so the resources-to-production ratio is high. In the proposed hybrid microgrid system, the main energy resources are solar and biomass, which will not run through in the future. So, these energy resources will not be depleted and resources the resources-to-production ratio will be much more than any fossil-based hybrid system. As a result, the overall system will be highly sustainable.

Table 8. GWP of gases

Pollutant	Emission (Kg/yr)	GWP	Total GWP
Carbon dioxide	760	1	760
Particulate matter	0.162	680	110.16
Unburned Hydrocarbons	0.238	25	5.95
Carbon Mono Oxide	2.14	1.9	4.066
Nitrogen Oxides	19.1	280	5348
			6228.176

3.5. Comparison analysis

A comparison study is presented in Table 9, which shows the performance of the designed system with previous works. From Table 9, it can be seen that hybrid microgrids have been designed for different countries worldwide. Several studies have also been done on renewable energy-based microgrid design for Bangladesh. However, most of the studies were based on a single energy source and have been analyzed for islands. A feasibility study for exploring the potential of available resources in generating electricity in the hill tracts of Bangladesh is necessary, which is performed in this paper. Here, a system is designed based on available renewable energy sources and conventional diesel generators and explores the optimized hybrid microgrid system. The cost of electricity for the developed optimized model is $0.0182/kWh, which is less than most of the previous works. Though optimization is done in almost all the earlier results, they lack sensitivity and sustainability analysis. Sensitivity analysis depicts the impact of variations in component cost on total energy cost. Sustainability analysis helps quantify and understand the impact on nature, the environment, the economy, and society. The sustainability analysis in this study verifies that the designed system is more effective with a high percentage of renewable energy share as well as low net energy import dependency.

Table 9. Comparison study with previous works

Ref	Energy used	Country	Cost of Electricity	Sensitivity analysis	Sustainability analysis
[14]	Solar	Iran	€0.452/kWh	×	×
[16]	Solar, wind	India	$0.675/kWh	×	×
[18]	Solar, PV, hydro, diesel	Turkey	$0.609/kWh	×	×
[19]	Grid+PV	India	$0.058/kWh	×	×
[21]	PV, diesel	Thailand	$0.20/kWh	✓	×
[23]	PV, wind, diesel	Algeria	$0.255/kWh	×	×
[26]	PV, biomass, diesel	India	$0.145/kWh	×	×
[27]	PV, wind, diesel	Malaysia	$0.279/kWh	×	×
[52]	PV, wind, diesel	Indonesia	$0.096/kWh	×	×
Proposed work	PV, hydro, biogas, diesel	Bangladesh	$0.182/kWh	✓	✓

4. CONCLUSION

This study aims to explore a microgrid system's feasibility and sustainability in the hill tracts of Bangladesh to meet the power demand. Naraichori, a remote area with no electricity access, has been chosen as a testbed. The site has been explored to find the available renewable energy resources, and the data have been used to simulate in the HOMER software. Different combinations of public resources are considered in the simulation process. Cost of generation has been the prime concern, along with sustainability and environmental conditions. Based on the simulation results, the hybrid system of PV/hydro/biomass/DG has been selected as the system to be installed because of its minimum generation cost of $0.182/KWh and 93% of electricity comes from PV modules, while 6%, 0.5% and 0.5% of electricity come from Hydro turbine, diesel generator, and biogas generator, respectively. This system emits 47, 54, and 117 times less CO_2 when compared to kerosene, national grid, and diesel-based systems per year. The optimized system is more suitable than the standalone solar home and national grid in the context of economic and environmental points of view. This study analyzed the optimized system against several sustainability indicators which have not been done yet for hybrid microgrid systems in hill tracts of Bangladesh. From sustainability indicators, it is found that this system has a higher renewable share of energy, around 99.5%. Furthermore, net energy import dependency is as low as 0.5%, and GHG production per energy usage is 0.06425 kg/KWh. All these indicate that this system is highly sustainable, considering different conditions. In the future, the study can be used for feasibility and sustainability analysis of other potential areas in Bangladesh as well as the whole world for energy generation from hybrid microgrids.

Data availability

The data that support the findings of this study are included within the article.

ACKNOWLEDGEMENTS

The authors thank the Chittagong University of Engineering and Technology (CUET) for providing support under the Development of the CUET Project and Project No. CUET/DRE/2022-23/EEE/017 under Directorate of Research and Extension (DRE), CUET and Universitas Airlangga, Indonesia for supporting this work through *Penelitian Dasar Unggulan* (PDU), grant code 414/UN3.1.17/PT/2023.

REFERENCES

[1] V. L. Pachapur, S. J. Sarma, S. K. Brar, Y. Le Bihan, G. Buelna, and M. Verma, "Biological hydrogen production using co-culture versus mono-culture system," *Environmental Technology Reviews*, vol. 4, no. 1, pp. 55–70, 2015, doi: 10.1080/21622515.2015.1068381.

[2] S. Palanisamy and H. Rajaguru, "Machine learning techniques for the performance enhancement of multiple classifiers in the detection of cardiovascular disease from PPG signals," *Bioengineering*, vol. 10, no. 6, 2023, doi: 10.3390/bioengineering10060678.

[3] A. Islam, K. F. Al-tabatabaie, A. K. Karmaker, M. Biplob Hossain, and K. Islam, "Assessing energy diversification policy and sustainability: Bangladesh standpoints," *Energy Strategy Reviews*, vol. 40, 2022, doi: 10.1016/j.esr.2022.100803.

[4] M. H. Masud, M. Nuruzzaman, R. Ahamed, A. A. Ananno, and A. N. M. A. Tomal, "Renewable energy in Bangladesh: current situation and future prospect," *International Journal of Sustainable Energy*, vol. 39, no. 2, pp. 132–175, 2020, doi: 10.1080/14786451.2019.1659270.

[5] S. Mohazzem Hossain, S. Biswas, and M. Raihan Uddin, "Sustainable energy transition in Bangladesh: Challenges and pathways for the future," *Engineering Reports*, pp. 1–26, 2023, doi: 10.1002/eng2.12752.

[6] B. K. Das, M. Hasan, and F. Rashid, "Optimal sizing of a grid-independent PV/diesel/pump-hydro hybrid system: a case study in Bangladesh," *Sustainable Energy Technologies and Assessments*, vol. 44, 2021, doi: 10.1016/j.seta.2021.100997.

[7] H. S. Roy, M. R. Sarker, and T. Ahmed, "Design and analysis of future hybrid micro grid system for Matiranga," in *2020 IEEE Region 10 Symposium*, 2020, pp. 896–899, doi: 10.1109/TENSYMP50017.2020.9230665.

[8] P. H. Shaikh, A. Shaikh, Z. A. Memon, A. A. Lashari, and Z. H. Leghari, "Microgrids: a review on optimal hybrid technologies, configurations, and applications," *International Journal of Energy Research*, vol. 45, no. 9, pp. 12564–12597, 2021, doi: 10.1002/er.6666.

[9] N. Karthik, A. K. Parvathy, and R. Arul, "A review of optimal operation of microgrids," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, pp. 2842–2849, 2020, doi: 10.11591/ijece.v10i3.pp2842-2849.

[10] R. Jabeur, Y. Boujoudar, M. Azeroual, A. Aljarbouh, and N. Ouaaline, "Microgrid energy management system for smart home using multi-Agent system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1153–1160, 2022, doi: 10.11591/ijece.v12i2.pp1153-1160.

[11] R. Muzzammel, R. Arshad, S. Bashir, U. Mushtaq, F. Durrani, and S. Noshin, "Comparative analysis of optimal power flow in renewable energy sources based microgrids," *International Journal of Electrical and Computer Engineering*, vol. 13, no. 2, pp. 1241–1259, 2023, doi: 10.11591/ijece.v13i2.pp1241-1259.

[12] G. Reina, M. Mauledoux, and O. A. Avilés, "Simulation of a microgrid for a non-interconnected zone that integrates renewable energies," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 1, pp. 201–216, 2021, doi: 10.11591/ijece.v11i1.pp201-216.

[13] S. A. Belfedhal, E. M. Berkouk, and Y. Messlem, "Analysis of grid connected hybrid renewable energy system," *Journal of Renewable and Sustainable Energy*, vol. 11, no. 1, 2019, doi: 10.1063/1.5054869.

[14] M. Mehrpooya, M. Mohammadi, and E. Ahmadi, "Techno-economic-environmental study of hybrid power supply system: a case study in Iran," *Sustainable Energy Technologies and Assessments*, vol. 25, pp. 1–10, 2018, doi: 10.1016/j.seta.2017.10.007.

[15] A. B. Awan, M. Zubair, G. A. S. Sidhu, A. R. Bhatti, and A. G. Abo-Khalil, "Performance analysis of various hybrid renewable energy systems using battery, hydrogen, and pumped hydro-based storage units," *International Journal of Energy Research*, vol. 43, no. 12, pp. 6296–6321, 2019, doi: 10.1002/er.4343.

[16] D. Kumar and T. Tewary, "Techno-economic assessment and optimization of a standalone residential hybrid energy system for sustainable energy utilization," *International Journal of Energy Research*, vol. 46, no. 8, pp. 10020–10039, 2022, doi: 10.1002/er.6389.

[17] N. Wehbe, "Optimization of Lebanon's power generation scenarios to meet the electricity demand by 2030," *Electricity Journal*, vol. 33, no. 5, 2020, doi: 10.1016/j.tej.2020.106764.

[18] M. Gökçek and C. Kale, "Optimal sizing of off-grid hydrokinetic-based hybrid renewable power systems for a house load demand," *International Journal of Energy Research*, vol. 45, no. 7, pp. 10208–10225, 2021, doi: 10.1002/er.6509.

[19] F. Ahmad and M. S. Alam, "Feasibility study, design and implementation of smart polygeneration microgrid at AMU," *Sustainable Cities and Society*, vol. 35, pp. 309–322, 2017, doi: 10.1016/j.scs.2017.08.007.

[20] F. Ahmad and M. S. Alam, "Economic and ecological aspects for microgrids deployment in India," *Sustainable Cities and Society*, vol. 37, pp. 407–419, 2018, doi: 10.1016/j.scs.2017.11.027.

[21] R. Khamharnphol *et al.*, "Microgrid hybrid solar/wind/diesel and battery energy storage power generation system: application to Koh Samui, Southern Thailand," *International Journal of Renewable Energy Development*, vol. 12, no. 2, pp. 216–226, 2023, doi: 10.14710/ijred.2023.47761.

[22] A. B. Culaba, A. J. R. Del Rosario, A. T. Ubando, and J. S. Chang, "Optimal design of an integrated renewable-storage energy system in a mixed-use building," *International Journal of Energy Research*, vol. 44, no. 12, pp. 9646–9658, 2020, doi: 10.1002/er.5488.

[23] Z. Belboul *et al.*, "Multiobjective optimization of a hybrid PV/wind/battery/diesel generator system integrated in microgrid: a case study in Djelfa, Algeria," *Energies*, vol. 15, no. 10, 2022, doi: 10.3390/en15103579.

[24] A. T. Dahiru and C. W. Tan, "Optimal sizing and techno-economic analysis of grid-connected nanogrid for tropical climates of the Savannah," *Sustainable Cities and Society*, vol. 52, 2020, doi: 10.1016/j.scs.2019.101824.

[25] M. B. Eteiba, S. Barakat, M. M. Samy, and W. I. Wahba, "Optimization of an off-grid PV/Biomass hybrid system with different battery technologies," *Sustainable Cities and Society*, vol. 40, pp. 713–727, 2018, doi: 10.1016/j.scs.2018.01.012.

[26] R. Rajbongshi, D. Borgohain, and S. Mahapatra, "Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER," *Energy*, vol. 126, pp. 461–474, 2017, doi: 10.1016/j.energy.2017.03.056.

[27] M. Hossain, S. Mekhilef, and L. Olatomiwa, "Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia," *Sustainable Cities and Society*, vol. 28, pp. 358–366, 2017, doi: 10.1016/j.scs.2016.10.008.

[28] M. Arefin, M. Raihan, H. Alvee, and M. Istiaque, "A study on feasibility of renewable hybrid power generation plant in Manpura Island," *Cuet.Ac.Bd*, vol. 2017, pp. 18–20, 2017.

[29] T. Chowdhury, H. Chowdhury, and A. Hasnat, "Feasibility of integrated pico hydro system at Choto Komoldoho, Mirsharai," in *International Conference on Mechanical, Industrial and Energy Engineering*, 2018, pp. 3–7.

[30] T. Chowdhury, H. Chowdhuyb, P. Chowdhury, and M. I. Miskat, "Feasibility study of hybrid renewable energy system for electrification of Kutubdia," in *International Conference on Mechanical, Industrial and Energy Engineering*, 2018, pp. 23–26.

[31] S. Salehin, A. K. M. S. Islam, R. Hoque, M. Rahman, A. Hoque, and E. Manna, "Optimized model of a solar PV-biogas-diesel hybrid energy system for Adorsho Char Island, Bangladesh," in *Proceedings of 2014 3rd International Conference on the Developments in Renewable Energy Technology*, 2014, pp. 1–6, doi: 10.1109/icdret.2014.6861692.

[32] P. Mazumder, M. H. Jamil, C. K. Das, and M. A. Matin, "Hybrid energy optimization: an ultimate solution to the power crisis of St. Martin Island, Bangladesh," in *2014 9th International Forum on Strategic Technology*, 2014, pp. 363–368, doi: 10.1109/IFOST.2014.6991141.

[33] M. M. Hossain, S. Barua, and M. A. Matin, "A pre-feasibility study for electrification in Nijhum Dwip using hybrid renewable technology," in *2015 International Conference on Electrical and Electronic Engineering (ICEEE)*, Nov. 2015, pp. 225–228, doi: 10.1109/CEEE.2015.7428262.

[34] S. K. Nandi and H. R. Ghosh, "A wind-PV-battery hybrid power system at Sitakunda in Bangladesh," *Energy Policy*, vol. 37, no. 9, pp. 3659–3664, 2009, doi: 10.1016/j.enpol.2009.04.039.

[35] I. Vera and L. Langlois, "Energy indicators for sustainable development," *Energy*, vol. 32, no. 6, pp. 875–882, 2007, doi: 10.1016/j.energy.2006.08.006.

[36] Y. Zhu, S. Chen, W. Huang, L. Wang, and G. Ma, "Complementary operational research for a hydro-wind-solar hybrid power system on the upper Jinsha River," *Journal of Renewable and Sustainable Energy*, vol. 10, no. 4, 2018, doi: 10.1063/1.5027758.

[37] D. Akinyele, J. Belikov, and Y. Levron, "Challenges of microgrids in remote communities: A STEEP model application," *Energies*, vol. 11, no. 2, pp. 1–35, 2018, doi: 10.3390/en11020432.

[38] A. Ataei, M. Nedaei, R. Rashidi, and C. Yoo, "Optimum design of an off-grid hybrid renewable energy system for an office building," *Journal of Renewable and Sustainable Energy*, vol. 7, no. 5, 2015, doi: 10.1063/1.4934659.

[39] T. Kamal, S. Z. Hassan, M. J. Espinosa-Trujillo, H. Li, and M. Flota, "An optimal power sharing and power control strategy of photovoltaic/fuel cell/ultra-capacitor hybrid power system," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 3, 2016, doi: 10.1063/1.4948926.

[40] A. Al-Karaghouli and L. L. Kazmerski, "Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software," *Solar Energy*, vol. 84, no. 4, pp. 710–714, 2010, doi: 10.1016/j.solener.2010.01.024.

[41] M. S. Ramli, S. S. A. Wahid, and K. K. Hassan, "A comparison of renewable energy technologies using two simulation softwares: HOMER and RETScreen," *AIP Conference Proceedings*, vol. 1875, no. 1, 2017, doi: 10.1063/1.4998384.

[42] S. Mandal, B. K. Das, and N. Hoque, "Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh," *Journal of Cleaner Production*, vol. 200, pp. 12–27, 2018, doi: 10.1016/j.jclepro.2018.07.257.

[43] S. Umar *et al.*, "A building integrated solar PV surface-cleaning setup to optimize the electricity output of PV modules in a polluted atmosphere," *Renewable Energy*, vol. 216, Nov. 2023, doi: 10.1016/j.renene.2023.119122.

[44] T. Zhang, W. S. Chandler, J. M. Hoell, D. Westberg, C. H. Whitlock, and P. W. Stackhouse, "A global perspective on renewable energy resources: Nasa's prediction of worldwide energy resources (Power) project," in *Proceedings of ISES World Congress 2007*, vol. 4, D. Y. Goswami and Y. Zhao, Eds. Berlin, Heidelberg, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 2636–2640.

[45] M. A. Shaikh, K. M. A. Chowdhury, S. Sen, and M. M. Islam, "Potentiality of wind power generation along the Bangladesh coast," in *AIP Conference Proceedings*, 2017, vol. 1919, doi: 10.1063/1.5018553.

[46] M. A. Wazed and M. A. Islam, "Prospect and future of biomass fuel: a review in Bangladesh perspective," *Engineering Transactions*, vol. 5, no. 2, pp. 61–66, 2010.
[47] P. Maher and N. Smith, "Pico hydro for village power a practical manual for schemes up to 5 kW in Hilly areas," *Development*, 2001.
[48] S. S. Patil and B. S. Chaudhari, "Wavelength converter based optimized RWA for all optical networks," *Asian Journal of Computer Science and Technology*, vol. 8, no. 2, pp. 111–115, 2019, doi: 10.51983/ajcst-2019.8.2.2131.
[49] J. J. Corbett and J. J. Winebrake, "Energy and GHG emissions savings analysis of fluoropolymer foul release hull coating," *Energy and Environmental Research Associates*, 2010.
[50] P. Raman, J. Murali, D. Sakthivadivel, and V. S. Vigneswaran, "Evaluation of domestic cookstove technologies implemented across the world to identify possible options for clean and efficient cooking solutions," *Journal of Energy and Chemical Engineering*, vol. 1, no. 1, pp. 15–26, 2013.
[51] D. Seok, S. Lee, M. Kim, J. Cho, and C. Kim, "Motion artifact removal techniques for wearable EEG and PPG sensor systems," *Frontiers in Electronics*, vol. 2, pp. 1–17, 2021, doi: 10.3389/felec.2021.685513.
[52] S. Syafii, P. Anugrah, H. D. Laksono, and H. Yamashika, "Economic feasibility study on PV/wind hybrid microgrids for Indonesia remote island application," *TEM Journal*, vol. 10, no. 4, pp. 2001–2006, 2021, doi: 10.18421/TEM104-66.

BIOGRAPHIES OF AUTHORS

Aditta Chowdhury has received his B.Sc. in electrical and electronic engineering from Chittagong University of Engineering and Technology. He is currently working as a lecturer in the same university. He has a research interest in machine learning, renewable energy. He can be contacted at email: aditta.eee@cuet.ac.bd.

Monirul Islam Miskat has graduated from Chittagong university of Engineering and Technology in 2019. He has Research interest in renewable energy, biofuel. He can be contacted at email: monirulislammiskat@gmail.com.

Tofael Ahmed has a Ph.D. from the University of Malaya, Malaysia. He is currently serving as a professor in the Department of EEE, Chittagong University of Engineering and Technology. His research interests include power system planning, transmission expansion planning, energy management and renewable energy integration. He can be contacted at email: tofael@cuet.ac.bd.

Shameem Ahmad has received his Ph.D. degree in electrical engineering from Universiti Malaya, Malaysia, in 2022. He is currently serving as an assistant professor in the Department of EEE, American International University-Bangladesh (AIUB). His research interests include microgrid, smart grid, power system control, power converter control. He can be contacted at email: ahmad.shameem@aiub.edu.

Md. Rifat Hazari serving as an assistant professor in Electrical and Electronic Engineering (EEE) Department at American International University-Bangladesh (AIUB). He has received B. Sc. Engg. and M.Sc. Engg. Degrees in Electrical & Electronic Engineering (EEE) from American International University-Bangladesh (AIUB) in August 2013 and December 2014, respectively and Ph.D. Degree in wind energy conversion and power system engineering from Kitami Institute of Technology (KIT), Japan in March 2019. His research interests include wind power and photovoltaic (PV)/solar power generation systems, microgrid, smart grid, HVDC. He can be contacted at email: rifat@aiub.edu.

Lilik Jamilatul Awalin was born in East Java, Indonesia, in 1977. She received the B.Eng. degree in electrical engineering in 1999 from the University of Widya Gama, M.Eng. degree in 2004 from the Institut Teknologi Sepuluh Nopember, Indonesia and Ph.D. degree in 2014 from Universiti Malaya. She was a senior lecturer in 2015-2020 in University Kuala Lumpur, electrical engineering section, British Malaysia Institute, Batu 8, Jalan Sg. Pusu, 53100, Gombak Selangor, Malaysia. Currently, she is senior lecturer in Airlangga University, Indonesia. Her research interests include fault location, protection system, distribution and transmission system, smart grid. She can be contacted at email: lilik.j.a@ftmm.unair.ac.id.

Saad Mekhilef is an IEEE and IET Fellow. He is a distinguished professor at the School of Science, Computing and Engineering Technologies, Swinburne University of Technology, Australia, and an honorary professor at the Department of Electrical Engineering, University of Malaya. He authored and co-authored more than 600 publications in academic journals and proceedings and five books with more than 45,000 citations, and more than 70 Ph.D. students graduated under his supervision. He serves as an editorial board member for many top journals such as IEEE Transaction on Power Electronics, IEEE Open Journal of Industrial Electronics, IET Renewable Power Generation, Journal of Power Electronics, and International Journal of Circuit Theory and Applications. He can be contacted at email: smekhilef@swin.edu.au.