

# Size Optimization and Sensitivity Analysis of Hybrid Wind/PV Micro-Grids- A Case Study for Bangladesh

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**ABSTRACT** This paper presents a feasibility and sensitivity analysis of renewable energy-based off-grid and grid-connected microgrids by investigating the potentials of wind and solar energy at different areas, namely, Kuakata, Sitakunda, Magnama, Dinajpur and Rangpur in Bangladesh - a country that experiences a tropical climate. A specialized neural network algorithm has been employed to track the wind speed and solar irradiance all year round in two salient regions and the promising results have been analyzed for making the decision whether the data are reliable for forecasting or not. Four different types of models including PV-Grid, Wind-Grid, Wind-PV-Grid, and off-grid hybrid renewables are designed using the Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software. By considering the key factors: net present cost, cost of energy, renewable fraction, local load demand, availability of renewable energy resources, system economics and greenhouse gas emissions, the optimal hybrid renewable energy system (HRES) configurations (Wind/PV/Grid/Battery) for the mentioned regions are determined. Various sensitivity and optimization variables, such as RE resources, local load demand, grid energy price, nominal discount rate, the life-time of wind turbine, the capacity of wind turbine, PV arrays, converter, and battery are used to make the decision. Detailed sensitivity analyses are performed to investigate how the optimal system configurations change with a tiny variation in input variables and results show output results are more sensitive on the variations in long-term average wind speed and solar irradiance, nominal discount rate, and the lifetime of wind turbines than the other inputs which is definitely a vital finding of this investigation. Finally, considering several decision making factors, a detailed feasibility chart is presented for two distinct nominal discount rates, i.e., 9% and 10%, which depicts the economically viable renewable energy based plant size in the mentioned regions. Although the crux of this paper is based on providing low-cost electricity to people living in rural areas of Bangladesh, our propositions carry with them certain concomitant benefits, not least of which are environmental and social benefits.

**INDEX TERMS** Cost of energy, net present cost, greenhouse gas, hybrid power system, plant size, wind, solar, renewable energy sources.

## I. INTRODUCTION

Every sector of the current world is highly dependent on energy, and about 80% of the total energy comes from fossil fuels and nuclear energy which are responsible for global warming [1]. At present, meeting the rapid growth of electricity demand is a major issue due to the high cost and

greenhouse gas (GHG) emission of conventional energy sources. The integration of renewable energy sources (RESs) is the most suitable and efficient solution to these problems, though they have some drawbacks due to their intermittency [2]. RESs added with conventional energy sources such as fossil fuels and energy storages can make the system more stable and reliable. In the absence of RESs, conventional energy sources and/or storage devices, such as batteries, act as a back-up device for continuity of power supply [2].

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As renewable energy (RE)-based hybrid systems, such as wind and solar photovoltaic (PV), have potential benefits compared to a conventional system, a huge amount of research and studies have been carried out on them.

The optimal design of a hybrid (wind/PV) standalone system has been analyzed based on economic and environmental aspects and it is found that if this design is adopted, CO<sub>2</sub> emission can be reduced by 24%, compared to the existing diesel-only system [3]. For remote residence, three different types of configurations have been analyzed and a comparative result based on the cost of energy (COE) and CO<sub>2</sub> emission has reported that a hybrid PV-diesel-battery system is more cost-effective than the other two models such as PV-diesel without storage, and diesel-only [4]. On the contrary, another study has shown that rural village is economically best suited for PV-diesel power generation system in the absence of energy storage systems [5]. For identifying the optimum model of PV-diesel-battery system in various climatic regions, some models have been developed by using C-programming language and HOMER software, and results have been shown on the basis of minimum net present cost (NPC) and CO<sub>2</sub> emission rates [6]. Authors in [7] have studied the economic feasibility of PV-diesel-battery power generation systems in various locations of South Africa and concluded that a hybrid power system has the superior characteristics than the base case system (diesel only). A brief comparison has been carried out with various models, namely PV-diesel hybrid system, stand-alone PV, and some others by considering variations in PV panel and diesel price, where based on the optimal analysis, the minimum COE has been found in PV-diesel hybrid system [8]. As a back-up source, diesel is only suitable for rural and remote areas where eco-friendly alternative sources such as batteries are limited. Moreover, considering economic and environmental effects, fossil fuels are not a good choice as hybrid system components.

To make the system more reliable, a combination of various RESs in one system is an ideal choice for green energy harvesting. By using HOMER and LINGO software, authors have studied and analyzed off-grid configurations for electrifying seven villages in the Almora district of India where, four different types of models have been considered with integrating biomass, hydro, solar, and wind energy sources and finally, the optimum results have been worked out [9]. A techno-economic analysis has been conducted on the basis of various system configurations and the experimental result has shown that an autonomous hybrid PV-wind energy system provides better performance than the PV-only and wind-only energy systems [10]. The authors in [11] have described wind energy-based power system model by analyzing the characteristics of wind turbine (blade length, cut in speed, rated speed, and shut-down speed), and have observed that due to insufficient wind speed, the designed model did not work properly in some areas of Pakistan; however, it did perform efficiently in Margalla hills. Therefore, it is important to analyze the potentials of RES in

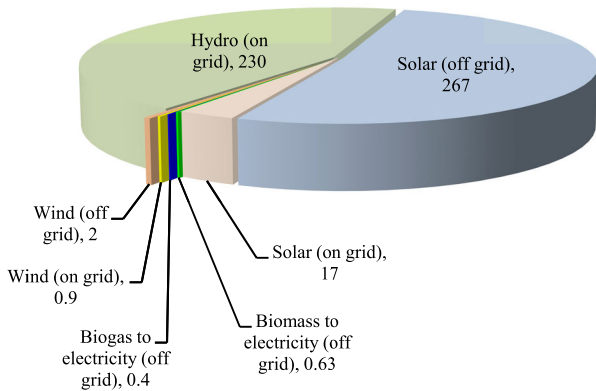
different locations for finding a suitable area for plant installation.

It is known that Bangladesh has a vast potential for RESs. Due to their intermittent nature and changes in load demand, renewable outputs do not always match with the time-varying load patterns [12]. As a consequence, there is a need for extra battery storage or other components for ensuring an uninterrupted power supply to the consumer. It has been learned that a hybrid PV/Wind/energy storage system is a reliable source of electricity [13]. Due to the high cost of battery energy storage, a stand-alone system is very expensive [14]. However, the issue related to the cost-benefit analysis of the grid-connected and the off-grid mode hybrid power system in Bangladesh has attracted much less attention in the literature. Moreover, the best mixture of renewable energy sources to reduce cost and GHG emission is still to be found out. Therefore, it is important to find out a suitable combination of different RESs to maximize the benefit which is the prime interest of this research.

Bangladesh is a developing country and with the rise in her population, the energy demand is also increasing rapidly. Nowadays, the energy crisis is the most vital problem in Bangladesh, and only a limited number of people have access to electricity in rural and remote areas [15], [16]. On the other hand, climate is an important issue for ecological balance. Although RESs have noteworthy potential, the implementation of grid-connected hybrid system has been slow to materialize. Advanced RE technologies with proper planning could meet massive power demand which will also reduce the dependency on foreign fuels and domestic natural gas. Bearing all this in mind, the contributions of this research are given below.

- To pinpoint the potentialities of renewable energy at various locations in Bangladesh.
- To determine the optimum hybrid RES configurations (Wind/PV/Grid/Battery) for the dominated regions by considering various sensitivity and optimization variables.
- To perform the sensitivity analysis for investigating the effect of uncertainty of key variables on the optimal system configuration and undoubtedly, it is a vigorous concern for HRESs design.
- To determine the economically viable plant size in the mentioned regions by considering various key factors
- To delineate the socio-economic and environmental benefits of renewable energy adoption.

This paper is organized as follows: Section 2 discusses the renewable energy scenario in Bangladesh; modeling parameters are presented in section 3; section 4 includes a description of the software tools that are employed, section 5 presents input parameters which are used for simulation; section 6 depicts the simulation results under various conditions; sections 7 and 8 delineate the economic and ancillary benefits of renewable energy and section 9 concludes the paper with pointers for future research directions.



**FIGURE 1. Installed RE share in Bangladesh [18]. Approximately 518 MW of electricity comes from RESs and 52% of this energy comes from the off-grid mode.**

## II. RENEWABLE ENERGY DEVELOPMENT IN BANGLADESH

As far as sustainability is concerned, RESs are the clear alternative available in the context of the current energy crisis situation. Though the environmental issue is not a vital factor for a lower GDP country like Bangladesh, insertion of renewable energy can reduce the dependency on natural resources which is in a state of continuous decline [17]. Bangladesh has a substantial potential for RE and significant past experience in developing RE-based projects. Most of the existing RE investments has been in off-grid technologies, such as solar home systems (SHS), solar micro-grids, and solar irrigation pumps. Figure 1 shows the present scenario of installed capacity in MW from different RESs in Bangladesh [16], [18]. Approximately 518 MW of electricity comes from RESs which is quite low as compared to the total installed capacity of this country [16], [18]. However, the government of Bangladesh has set several investment targets for grid-connected technologies including utility-scale solar, wind, and waste-to-energy [15]. In this paper, only solar and wind power system have been analyzed for their superior characteristics and availability at local conditions.

### A. SOLAR ENERGY

Around the world, solar energy is now considered as one of the most promising sources with the highest potential to gain energy compared to other RESs [19]. The geographical location of Bangladesh makes her an ideal candidate for solar energy harvesting and this tropical country receives an average of 4–6.5 kWh/m<sup>2</sup> solar irradiance daily [17], [20]. This can produce a total of  $1018 \times 10^{18}$  J of energy which is thousand times higher than the current energy demand [20]. Although concentrating solar power is in its emerging stage, other technologies are growing rapidly in Bangladesh. Among them, solar home system (SHS) is the most effective one with more than 5.2 million SHSs installed around the country [18], [21]. On the other hand, with the advancement of technology, grid-connected solar systems are integrated into several areas of the country. Roof-tops of commercial and residential buildings can be utilized by

installing solar PV to meet the basic demand and to support the grid by supplying the surplus electricity. A total of 14.59 MWp solar roof-top PV systems were installed. Furthermore, for achieving vision 2021 (2000 MW renewable power generation added to the national grid) [16], [18], [21], considerable investment projects have been commenced [16]. However, this is not adequate for achieving the proposed goal. Additional plant sites and planning procedures are duly required.

### B. WIND ENERGY

A wind energy system, in terms of fuel diversity, is one of the most promising RES, though it is highly dependent on geographical location. Implementing a large-scale wind farm is feasible when wind speed is observed to be above 7 m/s and for a small wind farm, 2.5 m/s is the starting wind speed condition [20]. The seaside area of Bangladesh is appropriate for the production of electricity from wind as there is strong wind flow coming from the Indian Ocean, especially during the monsoon. Due to lack of wind speed data, uncertain weather conditions and lack of planning, a significant advancement of wind power generation is not seen. Only three wind farms are installed with a combined capacity of 2.9 MW which is quite low compared to other RES. The country's first grid-tied wind turbine power plant with a capacity of 0.9 MW (4x225 kW) was installed by the Power Development Board (BPDB) at Muhuri Dam, Feni. And then, a 1000 kW Wind-Battery Hybrid Power plant (5x20 kW) has been implemented at Kutubdia in 2008. Moreover, in recent years, another Wind Power Plant of Capacity 1000 kW has been successfully implemented on the Turnkey Basis at Kutubdia Island, Cox's Bazar. More importantly, BPDB has taken systematic steps to implement renewable energy-based projects and to promote energy efficiency measures from 2009 onwards to achieve the policy target. As a consequence, three mega projects (grid-connected wind power plant)- totaling a capacity of 162 MW- are undertaken in different locations of Bangladesh [16].

## III. SYSTEM MODELLING

In broad strokes, the modeling of the entire system is predicated on a two-pronged approach: (1) Components Modeling and (2) Economical Aspects Modeling. The system components aid in projecting the net electricity production, whereas the economic model helps us in determining whether a proposed model is feasible or not. There is always a trade-off between electricity production and accrued cost. Hence, the system output variables are pitted against the economical parameters to find the optimum configuration, renewable ratio and size optimization of the proposed plants.

### A. SYSTEM COMPONENTS MODELING

The 5 prominent locations are amenable to two major RESs: wind and solar energy. This *a priori* assumption is based on empirical data [16]. Hence, the solar PV and wind turbine modeling parameters and equations are outlined below.

1) SOLAR PV MODELING

The output power of a solar PV cell can be calculated using the following equation [22]:

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{I_T}{I_S} \right) [1 + \alpha_P (T_c - T_s)], \quad (i)$$

where,  $Y_{PV}$  is the rated capacity of the PV array,  $f_{PV}$  indicates PV derating factor,  $I_T$  is the incident solar radiation,  $I_S$  represents incident solar radiation under standard test conditions ( $1 \text{ kW/m}^2$ ),  $\alpha_P$  denotes temperature co-efficient of power,  $T_c$  is PV cell temperature,  $T_s$  is PV cell temperature under standard test conditions ( $25^\circ\text{C}$ ).

The derating factor helps account for the reduction of output power due to various environmental conditions, i.e. dust accretion over the panel surface, aging, wiring loss, and shading. A derating factor of 90% is considered in this analysis to simulate realistic conditions.

2) WIND TURBINE MODELING

In order to quantify the wind energy potential, wind power density is a good indicator which encapsulates the effect of wind speed distribution and its dependence on wind speed and air density. The wind power available per unit area swept by the turbine blades is given by the following equation [23]:

$$P_t = 0.5 \rho C_P \sum (V_i^3 t_i), \quad (ii)$$

where,  $V_i$  = Mean Wind speed for the  $i$ -th time interval (i.e. 10 minute or hourly basis),  $t_i$  = Ratio of the number of hours corresponding to the chosen time interval to the total number of hours,  $C_P$  = Power co-efficient of the wind turbine provided by the manufacturer,  $\rho$  = air density.

Air density can be calculated from the following equation:

$$\rho = \frac{P}{RT}, \quad (iii)$$

where  $P$  is air pressure ( $Pa$ ),  $R$  is gas constant ( $J/kg/k$ ) and  $T$  is the ambient temperature ( $K$ ).

A wind turbine produces power between cut-in wind speed,  $V_{ci}$ , and cut-out wind speed,  $V_{co}$ . Wind turbine output between rated wind speed,  $V_r$ , and the cut-out wind speed,  $V_{co}$ , is usually assumed to be constant. But wind speed varies with height and we have to take it into consideration. Wind speed at various elevation is calculated using the following expression [22]:

$$V = V_{ref} \left( \frac{H}{H_{ref}} \right)^\alpha, \quad (iv)$$

where,  $V_{ref}$  is wind speed at reference height  $H_{ref}$ . And  $\alpha$  is the corrective exponent that accounts for surface roughness, wind speed, temperature, time of day and season. The value of  $\alpha$  is generally assumed to be  $1/7$ . Figure 2 shows the variation of wind speed with increasing elevation at Magnama, Cox's Bazar, as observed in September 2017 [24].

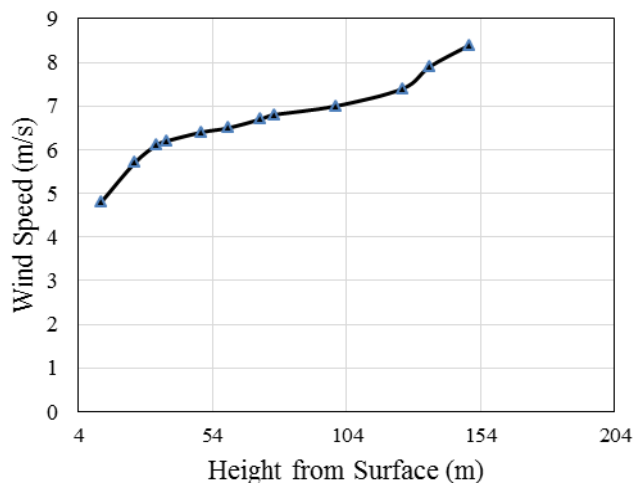


FIGURE 2. Wind speed at various heights in Magnama, Cox's Bazar as observed in September 2017 [24].

B. ECONOMICAL PARAMETERS MODELING

The cost parameters associated with renewable power generation are described in this section. The NPC means the existing value of all components that are connected in the plant minus the present value of all the revenues that it receives over the lifetime [25]. The total NPC in a year is called the total annualized cost. It is expressed as [25]:

$$C_{yr,total} = CRF(i, R_{plant-life}) * C_{NPC,Total}, \quad (v)$$

where  $C_{NPC,total}$ ,  $i$ ,  $CRF$ ,  $R_{plant-life}$  represents the total NPC in dollar, the annual interest rate, capital recovery factor and the plant lifetime in year, respectively. The capital recovery factor is a ratio of a constant annuity to the present value of receiving that annuity for a given year and it is used to calculate the present value of an annuity. It is expressed as:

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

where,  $i$  represent the annual interest rate and  $n$  is the number of years.

The COE is defined as the mean value of cost per kWh of useful electrical energy produced by the plant. Total electrical loads are divided into AC primary load and DC primary load. It is calculated by the following equation [25]:

$$COE = \frac{C_{yr,total}}{AC_{load} + DC_{load}}, \quad (vii)$$

where,  $C_{yr,total}$  is total annualized cost,  $AC_{load}$  is AC primary load and  $DC_{load}$  is DC primary load. It would be impractical to rely solely on the renewable power output for the provision of electricity for the entire region. Hence, an appreciable amount of electricity is expected to be provided by the utility. The energy from the grid,  $D_{grid}$ , is calculated using the following simple piecewise equation:

$$D_{grid} = \begin{cases} 0, & D \leq E_{gen} \\ D - E_{gen}, & D > E_{gen} \end{cases}, \quad (viii)$$

where  $D$  is the energy demand of the location and  $E_{gen}$  is the energy generated by the hybrid plant.

**IV. SOFTWARE TOOL AND METHODOLOGY**

The optimal design and techno-economic feasibility analysis of HRESs have been carried out by using a software tool called HOMER Pro (version 3.11.2) which is developed by the National Renewable Energy Laboratory (NREL). As HOMER Pro is a world-recognized professional micro-grid analysis tool, massive research works have been done by using it for outlining the optimum performance of the RE-based hybrid system in off-grid and on-grid modes [26]–[30]. Various input parameters, such as components of the hybrid system with their economic and technical characteristics, local electric or heating load demand, RE data, system economics, and constraints and variability factors are needed to perform the techno-economic analysis by using this software [31]. The optimization of system design configuration is performed by minimizing the objective function, i.e. NPC, to the system constraints, such as power balance, load management, and renewable fraction. Before implementing the microgrid systems, HOMER executes the viability study and optimization. Calculating the optimized system characteristics can be made in three stages, i.e. running the simulation, sensitivity analysis and optimizing the model. Before running the HOMER simulation, different assessments were done as a task of Pre-HOMER analysis. First of all, a detailed annual electric load demand of the proposed region was prepared by estimating and analyzing the collected load data. In that case, two random variability factors were used which make the load profile more practical. Secondly, resources data were collected from different references and a specialized neural network algorithm has been employed to track the resource data all year round. The microgrid system model has been designed by using HRES components which is available in this software. The system components cost data along with technical specification and system economics value were used to design the optimized system. After modeling the HRESs, the output of pre-HOMER assessment tasks was fed into the software tool for techno-economic analysis of hybrid renewable energy microgrids for the mentioned regions. Sensitivity and optimization variables were considered for this analysis. A detailed workflow of this analysis using HOMER Pro microgrid analysis tool is shown in Figure 3.

**V. INPUT PARAMETERS USED FOR SIMULATION**

**A. LOAD PROFILE**

Load estimation is an essential part of the simulation. The estimation was done for this research based on previously made case studies and reports for rural electrification in different countries [32]–[42]. Detailed load estimation procedures can be found in [43]. In this paper, the electricity consumers are divided into ten categories. Aiding DESCO load calculator [44], the consumption value for each type of load

**TABLE 1. Electricity unit consumption by different categories of consumers (kWh/day).**

Categories	Light	Ceiling Fan	TV sets	Computer	Iron	Rice cooker	Refrigerator	Water pumps	Lab equipment	Consumption (kWh/day)
High class house hold	6	3	1	1	1	1	1	1	-	13
Medium class house hold	4	2	1	-	-	1	-	-	-	3.64
Low class house hold	4	2	1	-	-	-	-	-	-	2.64
School	15	15	-	1	-	-	-	1	-	6.1
Health centre	8	8	1	-	-	-	1	1	1	23.21
Shops	2	1	-	-	-	-	1	-	-	6.84
Street light	-	-	-	-	-	-	-	-	-	1
Irrigation pump (1.5 HP)	-	-	-	-	-	-	-	-	-	8.8
Battery run auto rickshaw	-	-	-	-	-	-	-	-	-	9.6
Tourist hotel	25	25	-	-	-	1	1	1	-	32

is calculated. Different types of electricity consumers, their equipment quantity and consumption scenario are shown in Table 1.

Our prime concern is to provide green energy to the rural and semi-urban community where the grid is available. The assumptions such as the number of different building types are made by analyzing some previous case studies [32]–[35], [39]–[42] and reports [36]–[38], [45]. Moreover, we visited rural electrification board office [46] and some areas in Kuakata in Bangladesh (case study 4) for load assumption as well as the number of building types. These load data are fed in HOMER software as input data. Additionally, we used a 10% hour to hour and day to day random variability for estimating the load demand more accurately. Though the accurate load demand forecasting might be different from the assumption the approximate assumption is made only for analyzing purposes. In this research, five regions have been selected for the case study and the load estimations of these regions are as follows:

*Case Study 1 {Dinajpur}*: The case study 1 of this research involves the load of an area of 300 households (averaging 5 people per household) located at Daptori Para, Dinajpur. Among them, 50 high class, 200 medium class, and 50 low-class households have been considered. In addition, 2 schools, one community health center, 50 commercial shops, 100 street lights, 90 irrigation pumps for the winter season have also been assumed. The total daily electricity demand at Daptori Para is estimated as 3032 kWh/day with a 10% random variability factor (day to day and hour to hour) and the load factor is calculated as 0.28.

*Case Study 2 {Magnama, Cox’s Bazar}*: For case study 2, 1200 families have been considered of which 100 are high class, 700 medium class and the rest of them are low class. Additionally, 50 shops, one community health center, one school, and 100 street lights have been included in the estimation for that region. According to the load estimation with a 10% random variability, daily average load is found to be 4029 kWh/day and the load factor is calculated as 0.26.

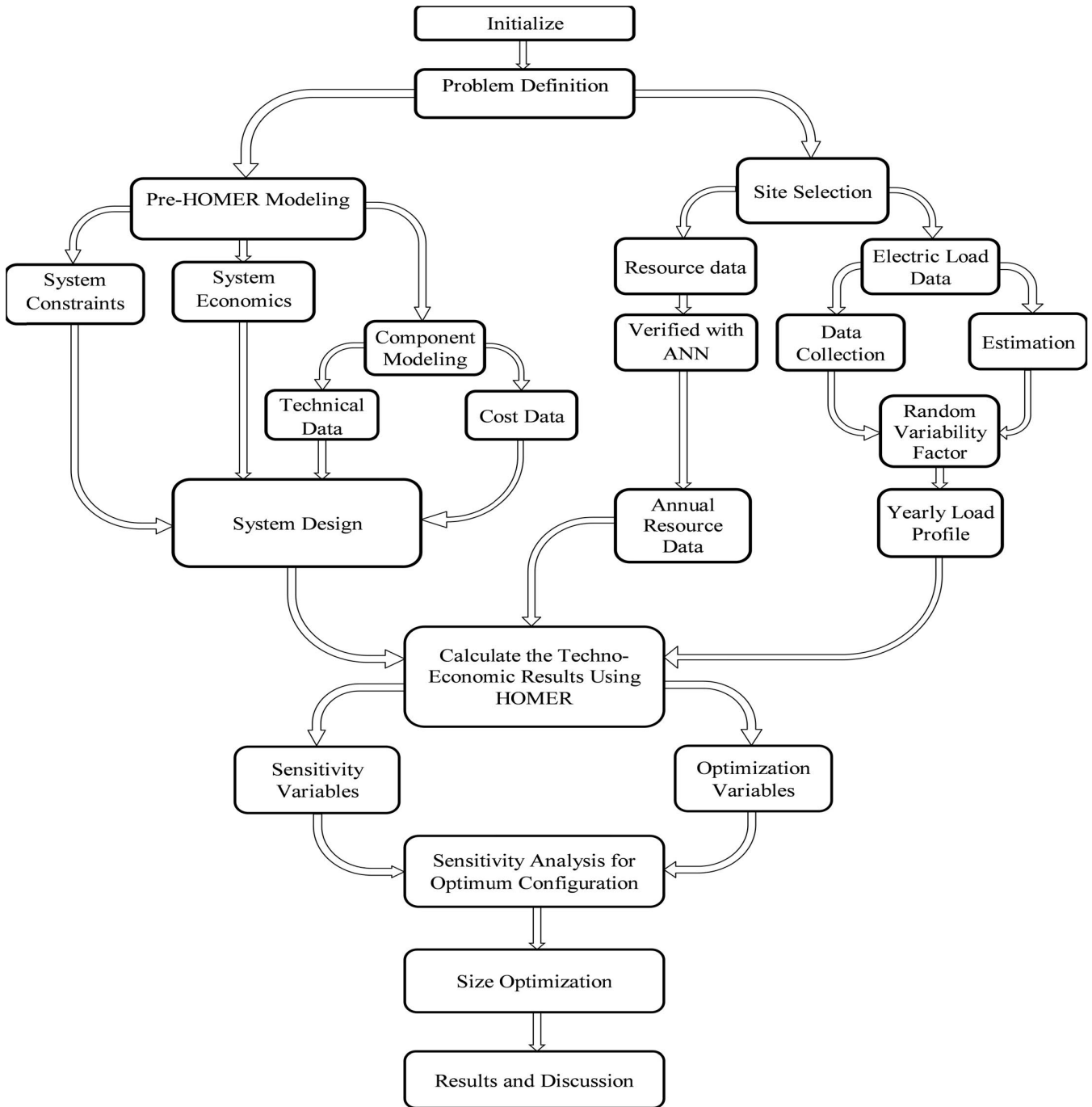


FIGURE 3. A schematic diagram describing the detailed methodology used for modeling and analysis.

Case Study 3 {Chilmari, Rangpur}: On a hypothetical basis, only 400 (200 medium class and 200 low class) households of Chilmari Char area have been considered for load estimation. After incorporating the random variability of 10%, the average primary load falls in the vicinity 2137 kWh/day while the load factor is calculated as 0.25.

Case Study 4 {Kuakata}: For load estimation, 200 families (50 high class and 150 low class), 50 shops, 15 tourist hotels, 200 battery-run auto-rickshaw, and 100 street lights

(100 W/light) have been considered for Kuakata region. Hourly load consumption scenario (estimated) for case study 4 are shown in Table 7 and 8 in the appendix. The combined load demand and load factor for Kuakata region can be calculated as 3512 kWh/day and 0.38, respectively.

Case Study 5 {Sitakunda}: At Sitakunda, 350 families (50 high class, 200 medium class, and 100 low class), one hospital, two tourist hotels, one school, and 60 irrigation pumps during the winter season have been considered. From

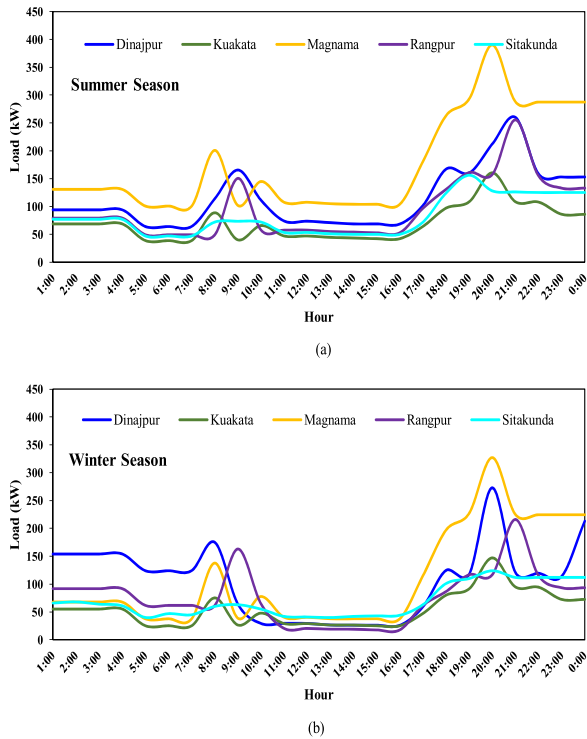


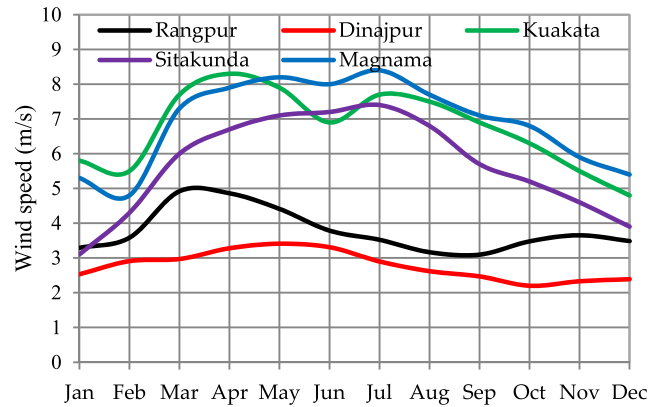
FIGURE 4. Estimated daily load profile of 5 selected sites of Bangladesh (a) summer season (b) winter season.

the load estimation; the average daily load is found 1778 kWh and the load factor is calculated as 0.34.

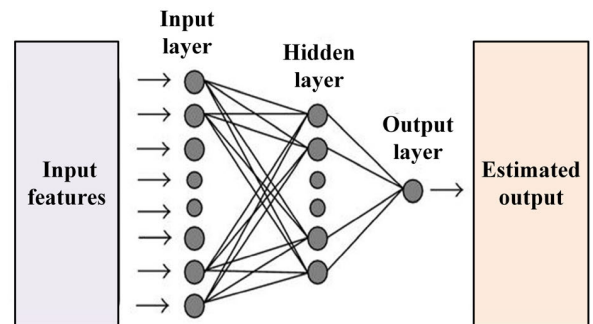
The total estimated electric loads, considering the listed appliances above, have been summed up to get the required load to be supplied by the system and which is shown in Figure 4.

**B. WIND RESOURCES**

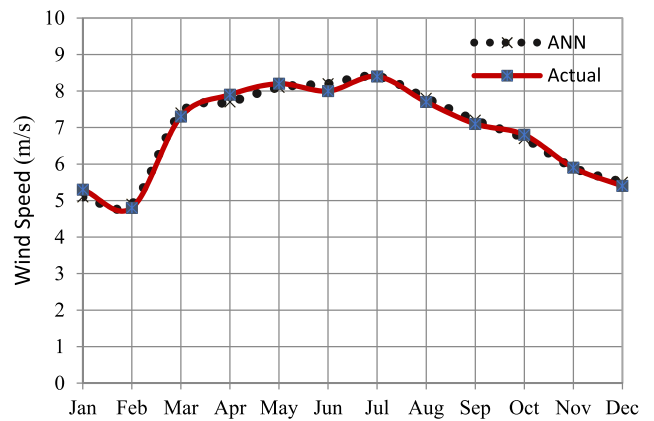
In this paper, wind characteristics and potential are analyzed for Kuakata, Sitakunda, Magnama, Dinajpur, and Rangpur. In Kuakata, higher wind speed is observed from April to September whereas it is much lower from October to March. The wind speed in Sitakunda and Magnama follows a similar pattern with the highest speed occurring in July. Dinajpur and Rangpur have relatively low wind speed over the year. Figure 5(a) shows the comparison of monthly average wind speeds for the above-mentioned five areas [47], [48]. Figure 5(b) and (c) takes Magnama as a test case to demonstrate the capability of Artificial Neural Network (ANN) to track the wind speed over the course of a year. ANN is a nonlinear model for prediction which learns through training that is used to tract the wind speed all year round to test the reliability. The model gleans information from a multitude of sources to feed dataset to the system [24]. A default network of three layers with 20 neurons is trained in MATLAB environment using Levenburg-Marquardt algorithm [49]. The total input dataset is divided into three sections randomly. 70%, 15 % and 15% of input data are used as training, validation and testing data respectively. 20 neurons or nodes present in the hidden layer are distributed as shown



(a)



(b)



(c)

FIGURE 5. (a) Monthly variation of mean wind speed at 50 m height in 2017 [24]. (b) A default 3-layer 20 neuron network is taken to train and the training of the network is designed in MATLAB with the Levenburg-Marquardt algorithm [49] taking Magnama as a test case. (c) Monthly mean wind speed tracking at 50m height in Magnama using Artificial Neural Network (ANN).

in Figure 5(b). They are connected with each and every nodes of both Input layer and Output layer. The “tansig” transfer function from MATLAB Neural Network toolbox is used at the input layer. The “purelin”, which is a neural transfer function is used at the output layer. Bias is also used during

training. As Figure 5(c) suggests, the tracking capacity of ANN is quite reliable and can be employed to forecast any looming intermittency of RES with an appreciable degree of precision.

### C. SOLAR ENERGY RESOURCES

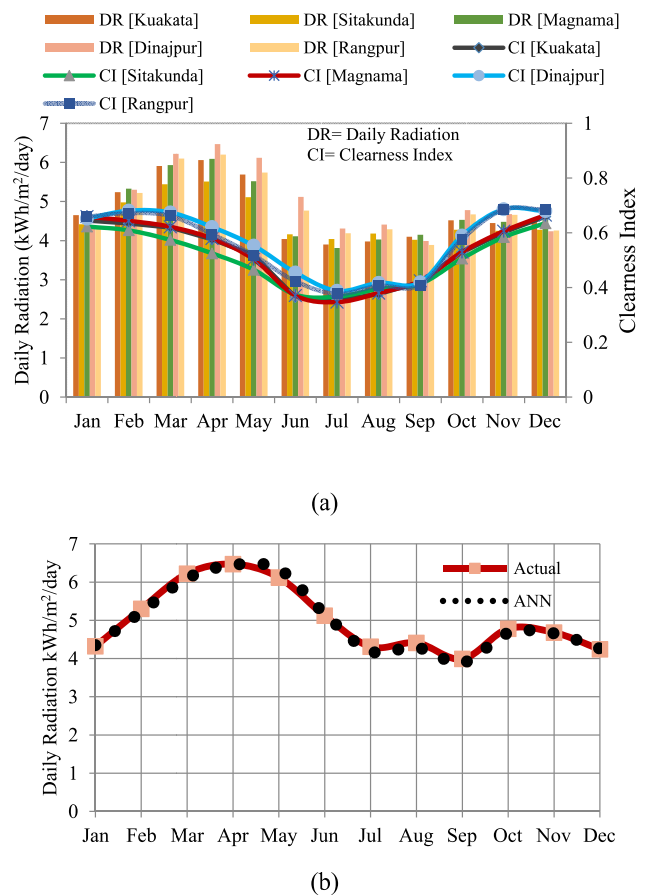
In this section, the data of monthly average daily solar irradiance ( $\text{kWh/m}^2/\text{day}$ ) and clearness index acquired through National Renewable Energy Lab and NASA surface meteorology and solar energy database are used as input to HOMER [47]. The annual average solar irradiance is estimated to be  $4.76 \text{ kWh/m}^2/\text{day}$  for Kuakata,  $4.56 \text{ kWh/m}^2/\text{day}$  for Sitakunda,  $4.77 \text{ kWh/m}^2/\text{day}$  for Magnama,  $5.00 \text{ kWh/m}^2/\text{day}$  for Dinajpur, and  $4.86 \text{ kWh/m}^2/\text{day}$  for Rangpur. The bar chart shows the monthly average daily solar irradiance ( $\text{kWh/m}^2/\text{day}$ ), and line graph indicates the clearness index for selected sites in Figure 6(a). It is found that the highest solar potential occurs in Dinajpur from February to July and the peak value observed is  $6.06 \text{ kWh/m}^2/\text{day}$  in April. On the other hand, the lowest solar potential is found in Sitakunda during September ( $4.02 \text{ kWh/m}^2/\text{day}$ ). In the winter season (from July to January), all these five locations have similar solar potential. In Figure 6(b), we take Dinajpur as a test case- due to its high solar potential- to study the capacity of ANN to track the average monthly solar irradiance over the course of a year. A default network of three layers with 20 neurons is taken to train. And the training of the network is done with the Levenburg-Marquardt algorithm [49]. Bias is also used during training. As the Figure shows, the forecasting capability is quite reliable and can account for the intermittent nature of the RES, which in this case, is solar energy.

### D. GRID PARAMETERS

The grid supplies power when there is no power from RE sources to meet the load demand. It also consumes power when additional RE power is available. The utility charge for grid power has two modes, the unit purchase price from the grid, and the sell-back price to the grid. This research is carried out by estimating a fixed rate which is the same as LCOE ( $0.10 \text{ \$/kWh}$ ) of this country [16]. In this paper, after observing the sensibility analysis result of different sell-back price values, a suitable fixed sell-back price is selected which is  $0.07 \text{ \$/kWh}$ .

### E. HYBRID SYSTEM DESIGN

In order to evaluate the system performance under different conditions, HOMER pretends the results of the grid-connected and the off-grid arrangements at the same area based on altered criteria such as the estimated connection cost, replacement cost, operation & maintenance cost, interest rate, and COE. The major components considered here are a wind turbine, PV, battery bank, and a power converter. For economic analysis, unit numbers, capital, replacement, operation & maintenance costs, and operating hours need to be declared in HOMER to perform the simulation.



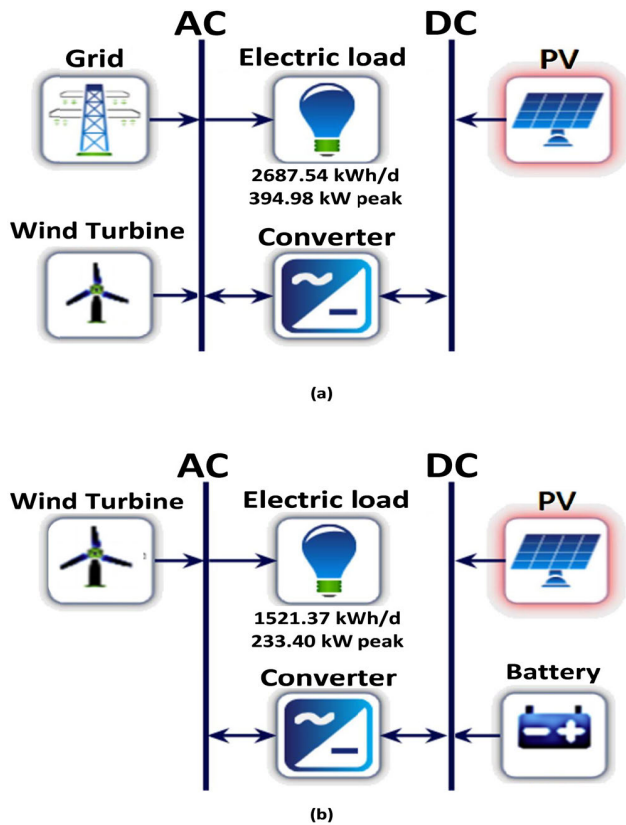
**FIGURE 6. (a) Monthly average solar irradiation and clearness index in 2017 [47]. (b) Monthly average solar irradiation tracking in Dinajpur using ANN. A default network of three layers with 20 neurons is taken to train. And the training of the network is done with the Levenburg-Marquardt algorithm [49].**

Figure 7 shows a typical grid-connected and stand-alone hybrid energy system.

**PV Module and Wind Turbine:** The capital cost of a solar PV module is taken as  $2000 \text{ \$/kWp}$  with a warranty of 25 years [50] and the replacement cost is estimated as 67% of its total capital cost. The operation & maintenance cost is  $26 \text{ \$/kWp}$  per year [15]. A derating factor of 90% is considered here to get realistic output. The permanent magnet generator (PMG) wind turbine has been selected for analysis due to its robustness [51]. In this paper, the capital cost of a wind farm is estimated as  $251759 \text{ \$/100 kW}$  [51]; replacement cost and operation & maintenance cost are taken as 75% and 2%, respectively, of the total capital cost. The wind turbine's costs include the costs of manufacturing, transportation, and installation of the turbine [52]. Detailed data of PV module and wind turbine are tabulated in Table 2 and 3.

**Inverter and Battery Bank:** In this study, the capital cost (factory gate price) of the inverter is taken as  $114 \text{ \$/kW}$  [54]. The replacement cost is 93 % of total capital cost and operation & maintenance cost is estimated at 1.2% of the capital cost [55]. For off-grid analysis, a generic 6-volt lithium-ion battery, with 1 kWh of energy storage capability, is used.





**FIGURE 7.** Block diagram of a typical hybrid microgrid model using HOMER Pro (a) On-Grid mode (b) Off-Grid mode. This micro-grid model incorporates Solar and Wind energy with the utility, due to them being the two dominant RESs.

**TABLE 2.** Details of PV module [53].

PV Parameters	Value
Manufacturer	Suntech
Model	STP210
Maximum Power at STC ( $P_{MAX}$ )	210W
Optimum Operating Voltage ( $V_{MP}$ )	26.4 V DC
Optimum Operating Current ( $I_{MP}$ )	7.95 A
Dimensions	1482 x 992 x 35 mm
Capital Cost	2000 \$/kWp
Replacement Cost	1340 \$/kWp
Operation & Maintenance Cost	26 \$/kWp
Derating Factor	90%
Slope	22.3 Degree
Lifetime	25 years
Search Space of PV capacity	50-250 kW (with an interval of 5 KW)

The capital cost of the battery is estimated at 200 \$/pc. The replacement cost is 85% of the total capital cost and operation & maintenance cost is 2.2% of that [55].

*Sensitivity and optimization variables:* For successful design and analysis of HRESs, systems need some control

**TABLE 3.** Details of wind turbine [51].

Wind Turbine Parameters	Values
Manufacturer	Kingspan Renewables Ltd.
Model	Proven 11 (kW6)
Rated Power	5.2 kW
Peak Power	6.1 kW
Cut-in Speed	3.5 m/s
Cut-out Speed	N/A(continuous operation)
Survival Wind Speed	70 m/s
Hub/Tower Heights	9m/15m/20m
Capital Cost of Wind Farm	251759 \$/100 kW
Replacement Cost of Wind Farm	181658 \$/100 kW
Operation & Maintenance Cost per Unit	500 \$/year
Lifetime	25 years
Search Space of WT number	0-30 units (with an interval of 1)

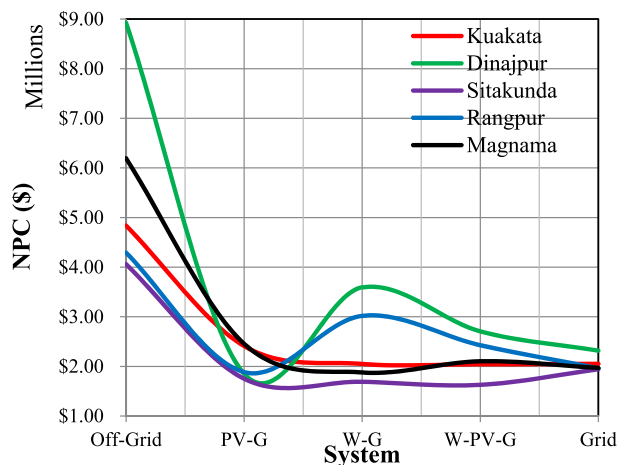
variables and constraints. Output results are very sensitive to these variables. The grid power price, the lifetime of a wind turbine, the average load demand, solar irradiance, wind speed values, and annual real interest rate are considered as sensitivity variables. A certain value of key variables ranging from 30% below to 30% above the best estimate is considered for sensitivity analysis. The search space of solar PV capacity, converter capacity, the number of wind turbines, and battery bank are considered as optimization variables. Here, search space range for PV module and converter is 0 to 3000 kW and for the wind turbine, it is 0 to 30 turbines with 100 kW of each. For battery bank, search space range was 0 to 20000 with 1 kWh each.

## VI. SIMULATION RESULTS AND DISCUSSIONS

In this study, off-grid and on-grid HRESs are designed by using HOMER Pro to meet the local load demand in the mentioned regions. To select the most techno-economically practicable system configuration, i.e., standard grid, grid-connected wind/PV, grid-connected wind-PV, and off-grid hybrid renewable energy systems, necessary performance factors, and sensitivity variables are considered. Then, for selecting the best mixture of Grid-PV-Wind for the specific location, different ratios of PV/Grid/Wind capacities have been simulated by inserting certain optimization variables, for example, PV capacity, converter capacity and the number of unit of the wind turbine. For acquiring the feasible RE plant size, the additional analysis has been performed by analyzing the sensitivity study and optimization results.

### 1) OPTIMUM SYSTEM CONFIGURATION

Analysis has been carried out by considering the other vital key factors, such as NPC, COE, renewable fraction, and greenhouse gas emissions to evaluate the optimum system model in the mentioned region to meet the desired load. After simulating the NPC value, COE and renewable penetration for all models for the selected locations are observed which



**FIGURE 8.** NPC vs. system configuration. The configuration ranges from off-grid, all to the grid-only. As is seen, different regions give values of NPC corresponding to different configurations. The optimum setting coincides with the lowest NPC.

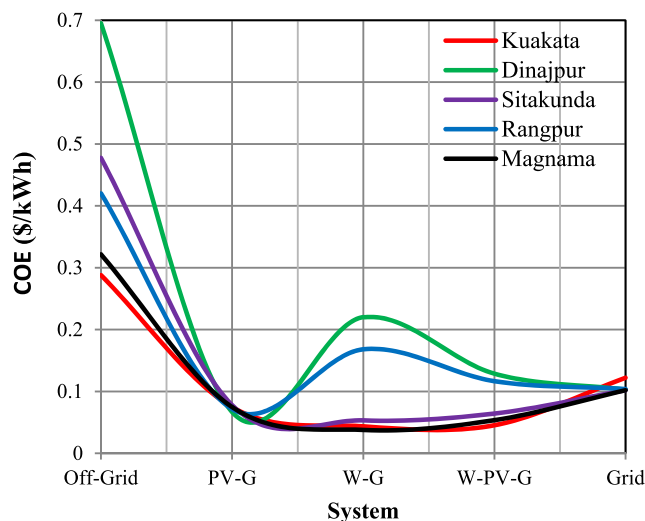
are presented in Table 4 and it shows that the minimum NPC and economically feasible energy generation cost for Magnama is given by the Wind-Grid (W-G) model and it is about \$1877869 and \$0.037, respectively. An 89% renewable fraction is found for this model though off-grid mode has 100% renewable fraction. However, it has quite high NPC and COE values. From this analysis, it can be said that, by considering NPC and COE, W-G model is superior to the other models for Magnama region. On the other hand, almost double NPC is required for W-G model than the PV-grid (PV-G) model in Dinajpur as it has high solar energy potential but a small difference of RF is observed in that region. For Kuakata region, among the five models, the value of NPC varies from \$2,043,668 to \$4,838,561 and the optimum solution is provided by the Wind-PV-Grid (W-PV-G) model. As for the Sitakunda region, similar model (W-PV-G) is observed as an optimum solution with a high degree of renewable contribution. For off-grid mode, relatively high values of NPC and COE are required for all regions. Figures 8 and 9 show the variations in NPC and COE for the selected five locations with respect to the various system configurations. It is seen that Dinajpur and Rangpur are best suited for solar energy harvesting whereas Magnama is most suitable for wind energy harvesting. A mix of solar and wind energy is the optimum solution for the other two locations (Kuakata and Sitakunda).

2) SIZE OPTIMIZATION

To optimize the system size, the designed HRESs with sensitivity and optimization variables were simulated by varying the number of wind turbines and PV capacity for both off-grid and on-grid mode for every mentioned region. In HOMER, search space, range of PV and converter capacity from 0 to 3000 kW and quantity of Wind turbine from 0 to 30 with having 100 kW each was used as optimization variables. The optimization results show that different regions, diverse

**TABLE 4.** Simulation results based on NPC, COE, and RF.

Model name	Location	NPC in US\$	COE in US\$/kWh	RF in %
Mag_W-G	Magnama	1877869	0.037	89.4
Mag_PV-G	Magnama	2455148	0.074	57.3
Mag_W-PV-G	Magnama	2103747	0.053	81.2
Mag_Off Grid	Magnama	6193812	0.321	100
Mag_Grid	Magnama	1969051	0.102	0
Kua_W-G	Kuakata	2049735	0.043	89
Kua_PV-G	Kuakata	2411836	0.074	53
Kua_W-PV-G	Kuakata	2043668	0.045	87.8
Kua_Off Grid	Kuakata	4838561	0.288	100
Kua_Grid	Kuakata	2051167	0.122	0
Din_W-G	Dinajpur	3589056	0.219	62.4
Din_PV-G	Dinajpur	1850822	0.066	68
Din_W-PV-G	Dinajpur	2706305	0.128	67.3
Din_Off Grid	Dinajpur	8925135	0.695	100
Din_Grid	Dinajpur	2316912	0.097	0
Sit_W-G	Sitakunda	1690032	0.053	96.8
Sit_PV-G	Sitakunda	1750795	0.077	74.5
Sit_W-PV-G	Sitakunda	1627833	0.064	93
Sit_Off Grid	Sitakunda	4060031	0.477	100
Sit_Grid	Sitakunda	1942627	0.097	0
Ran_W-G	Rangpur	3018317	0.168	81
Ran_PV-G	Rangpur	1884952	0.071	73.5
Ran_W-PV-G	Rangpur	2427268	0.116	79
Ran_Off Grid	Rangpur	4293792	0.420	100
Ran_Grid	Rangpur	1963214	0.104	0



**FIGURE 9.** COE (\$/kWh) vs. system configuration. It is seen that Dinajpur and Rangpur are best suited for solar energy harvesting whereas Magnama is most suitable for wind energy harvesting. A mix of Solar and wind energy is the optimum solution for the other two locations (Kuakata and Sitakunda).

weather conditions, local load demand, and system economics affect the optimum solution. For example, mixes of Wind-PV-Grid with certain ratios are the optimum solution for Kuakata and Sitakunda while grid-connected Wind

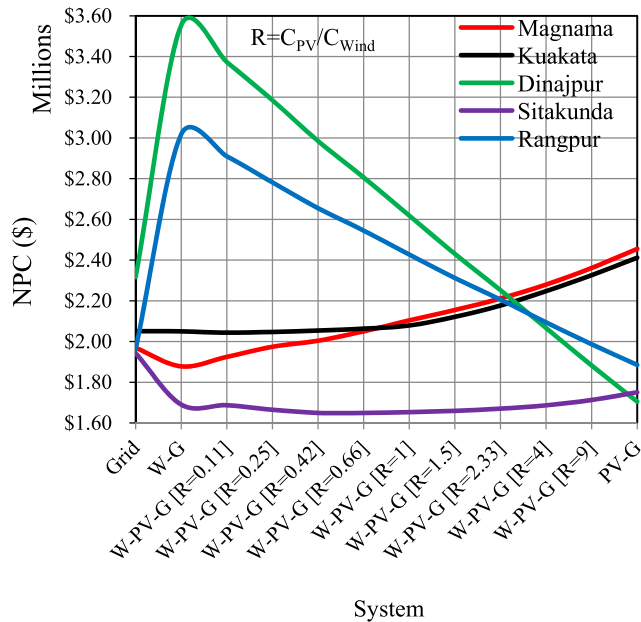


FIGURE 10. NPC as a varying function of PV-Wind-Grid mix system models.

system with certain value is suited for Magnama region. Based on optimization variables, a detailed optimization results of every designed model is plotted for the mentioned regions to evaluate the effectiveness of diverse weather conditions and load characteristics on size optimization which is shown in Figure 10. From this Figure, it is clear that Dinajpur has the highest solar potential. As a consequence, the NPC value for W-G model goes up almost twice as much as a standard grid and PV-G model. With the increase of PV contribution, the NPC value decreases gradually from  $R = 0.11$  to  $R = 9$  where  $R$  indicates the PV to wind capacity ratio and finally, the lowest NPC have found in PV-G model for this area. A similar result is found for the Rangpur region. On the other hand, the reverse scenario has been observed for Magnama region where W-G model gives the minimum value of NPC. This results also indicate that both W-G and W-PV-G models are economically feasible within the Wind to PV ratio interval of  $R = 0.11$  to  $R = 0.66$  for Kuakata region. Different results are observed for Sitakunda where all the models have lower NPC compared to the standard grid system as shown in Figure 10.  $R = 0.66$  gives the optimum result for Sitakunda compared to the other models.

The size optimization results also give the most feasible plant capacity in terms of wattage, which is shown in Figure 11. In this case, the performance matrix was NPC, COE, and local load demand and weather conditions. As is seen from the Figure, in most of the cases, economically feasible plant size can be as big as 1 MW, except for in Dinajpur region. For the Dinajpur region, the plant can be enlarged up to 2 MW. For example, in Kuakata, the NPC value is found to be \$2051167 for the grid-only system but for “0.5 MW W-PV-G ( $R = 0.11$ )” model it falls down to \$1624312. Almost similar NPC value as the standard grid is

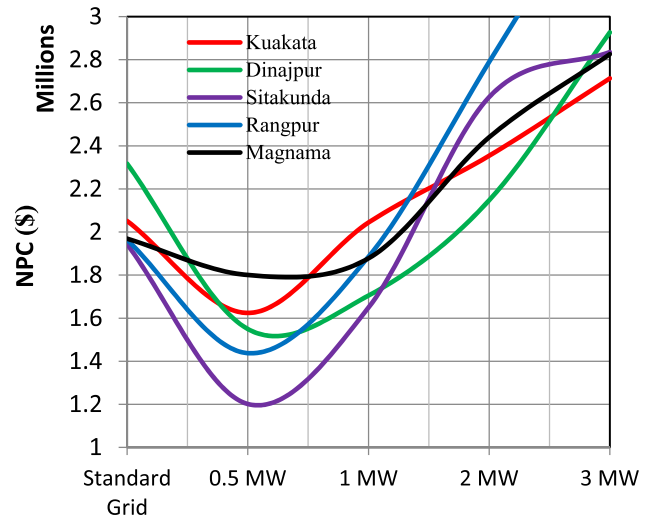


FIGURE 11. Convergence on the optimum plant size in terms of wattage based on NPC values.

required for meeting the same load by a 1 MW plant. It is also shown that the NPC increases exponentially as the plant size increases beyond 1 MW which was shown in Figure 11.

### 3) UNCERTAINTY IN KEY VARIABLES

Certainly, uncertainties in key variables make difficulties for the micro-grid system designer. The designer might be benefited by sensitivity analysis which shows the effect of uncertainty for making good design decisions. For instance, for performing micro-grid analysis, the grid energy price \$0.10/kWh over the lifetime of a plant is assumed. Undoubtedly, there is considerable uncertainty in grid energy price, but some other important input variables may be uncertain, such as long-term average wind speed and solar irradiance at the proposed regions, nominal discount rate, the lifetime of the wind turbine, and even average local electric load demand. Sensitivity analysis can help the modeler to evaluate the effectiveness of these uncertain input parameters on the performance, viability, robustness, and economics of a specific system configuration; and how the optimal system configuration changes across the range of uncertainty.

The spider graph in Figure 12 illustrates the outcomes of a sensitivity analysis on six variables. For fixed system configuration i.e. W-PV-G system, we entered manifold values (ranging from 30% below to 30% above the best estimate) for six uncertain input variables: the nominal discount rate, the grid energy price, the wind turbine lifetime, average wind speed, solar irradiance, and the average electric load. Figure 12 demonstrates how sensitive the total NPC is to each type of the uncertain variable and the relative steepness of the six curves delineates that the total NPC is more sensitive to the nominal discount rate, average wind speed, and wind turbine lifetime than to the other three variables. Certainly, such information can help a system designer to form the restrictions of a confidence interval or to prioritize efforts to reduce uncertainty.

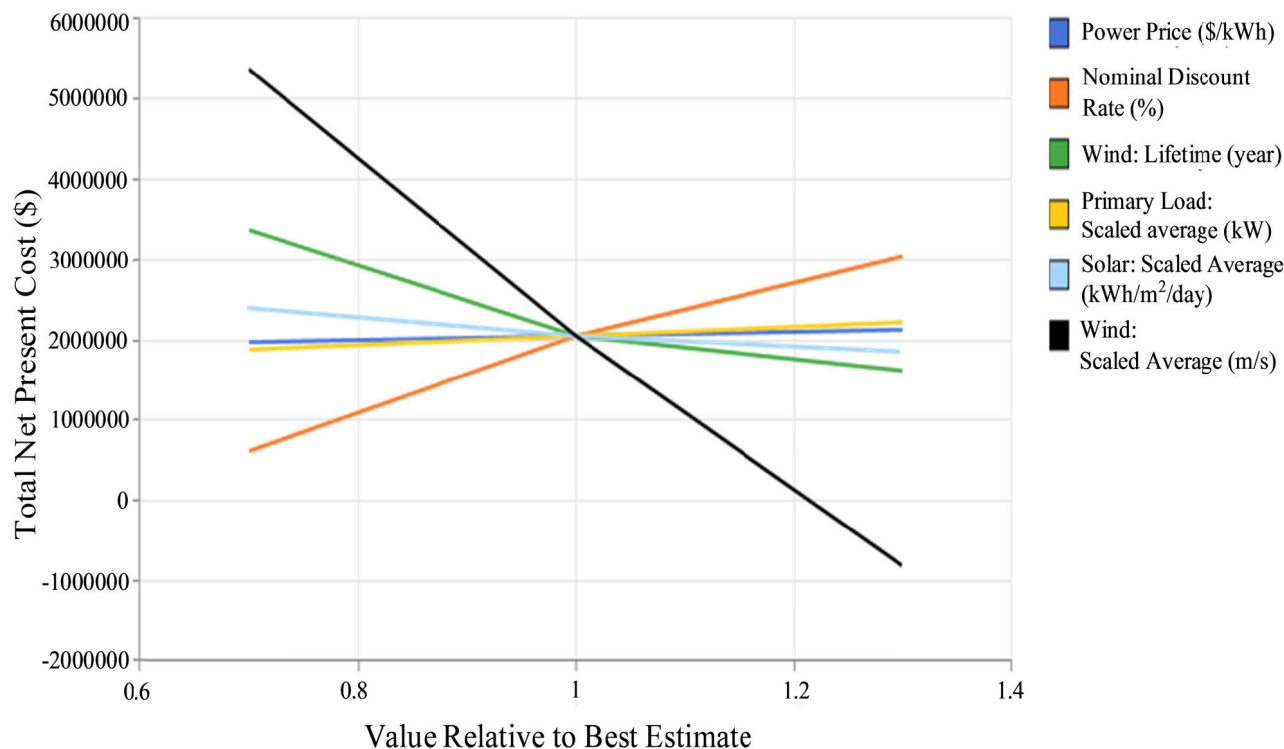


FIGURE 12. The graph illustrates the effect of variations in six key sensitivity variables.

#### 4) SENSITIVITY ANALYSIS RESULTS

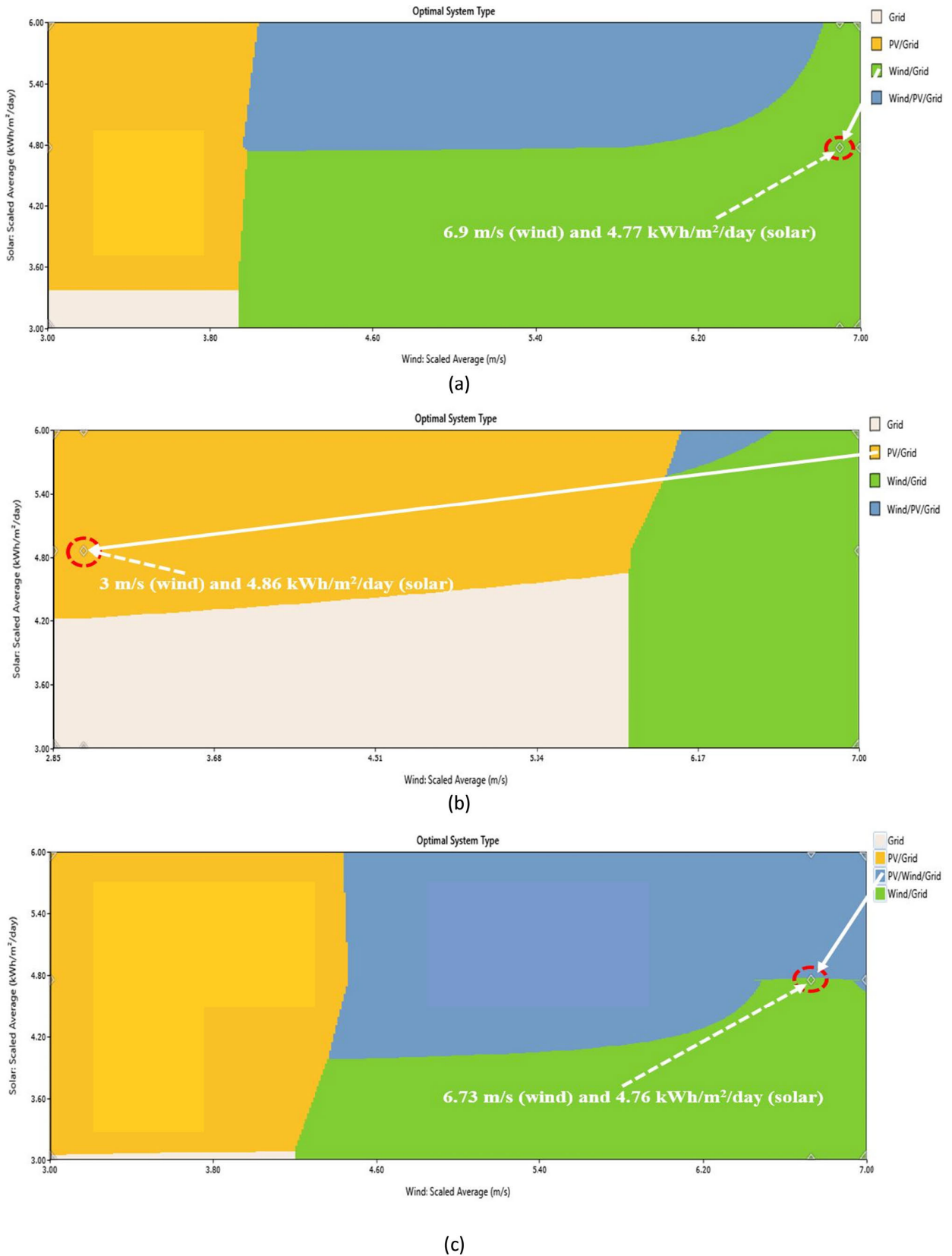
The renewable energy sources, such as solar and wind, are intermittent in nature. Therefore, different values of solar irradiance and wind speed are considered as the sensitivity variables which definitely help to select the optimum system configuration. For sensitivity analysis, wind speeds were varied from 3 to 7 m/s and solar irradiance from 3 to 6 kWh/m<sup>2</sup>/day for each location. Figure 13 shows how the system configuration is changed with an uncertain value of RE resources. In Figure 13(a), it can be seen that with the variation of renewable energy resource, four different types of optimum system configurations are found for Magnama region. The only the grid system is feasible for a lower value of renewable energy sources. The PV-grid system is optimum when the solar irradiance lies between 3.4 to 6 kWh/m<sup>2</sup>/day and the wind speed is found up to approximately 4 m/s.

Further increases the value of wind speed, the optimum system configuration is changed from PV-Grid to Wind-Grid for a certain range of solar irradiance which is shown in blue color in Figure 13(a). The W-PV-G is optimum when the solar irradiance is observed beyond 4.4 kWh/m<sup>2</sup>/day and wind speed lies between 4 to 6.5 m/s in combination. As the amount of solar irradiance was observed 4.77 kWh/m<sup>2</sup>/day and wind speed was 6.9 m/s in Magnama, W-G system configuration is the optimum in that location which indicates in the red circle in Figure 13(a). In a similar way, the PV-G system configuration is most suited in Rangpur region which is shown in Figure 13(b). For Kuakata region, a mix of W-G and

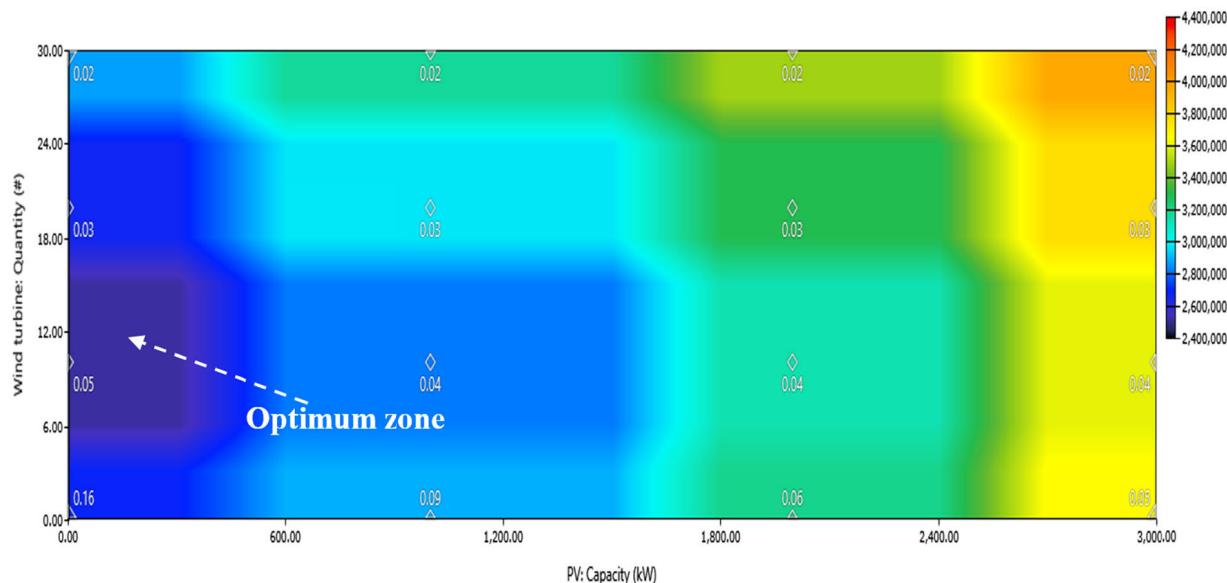
W-PV-G is an optimum solution as depicted in Figure 13(c). Similarly, a mix of W-PV-G is optimum for Sitakunda.

Figure 14 shows the results of a second sensitivity analysis on the W-PV-G system. We integrate this analysis to see whether the nominal discount rate, identified in Figure 12 as one of the most important of the uncertain variables, affects the optimal system configuration or not. For two different nominal discount rates, i.e., 9 % and 10%, the optimization surface plots for Kuakata region are shown in Fig. 14, where total NPC was the primary value and COE was the superimposed value. From this Figure, it is seen that with as the nominal discount rate decreases, the optimum zone on the optimization surface plot is changed. A mix of wind turbine (quantity ranges from 6 to 15) and PV (capacity ranges between 0 to 300 kW) with grid systems give the optimum solution for 10% nominal discount rate which is shown in Figure 14(a). However, with the decrease of the nominal discount rate by 1%, the contribution of wind turbine capacity increases significantly from 15 to 25 in quantity while keeping the PV capacity at a constant value which is shown in Figure 14 (b). Therefore, the optimum ratio of PV-Wind, as well as feasible plant size, varies with changing the nominal discount rate. Thus, system economics are the vital factor for size optimization of HRESs.

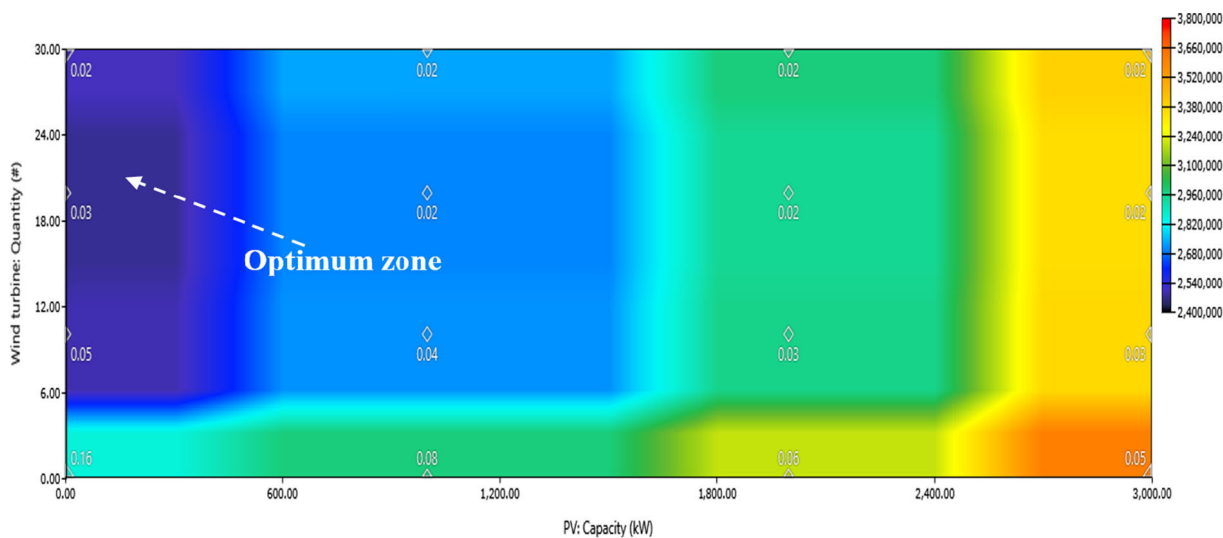
If the NPC value of the hybrid system model exceeds the grid’s NPC value, it is not an optimum choice. Employing this simple heuristic, an approximate feasibility chart for the five locations is outlined in Table 5. By considering



**FIGURE 13.** Optimum system type plot for (a) Magnama (b) Rangpur (c) Kuakata. As is seen, different regions give different optimum configurations. The optimum setting coincides with the lowest NPC.



(a)



(b)

**FIGURE 14. Optimization surface plot with NPC and COE superimposed for Kuakata region (a) for 10% nominal discount rate (b) for 9% nominal discount rate.**

sensitivity analysis and size optimization results, an approximate feasible plant size for both nominal discount rates is predicted in Table 5. This feasibility chart has been made by considering only economic aspects. If environmental issues are incorporated into the decision matrix, this result may vary considerably. This issue is tackled in the following section.

**VII. ECONOMIC AND ENERGY BENEFITS**

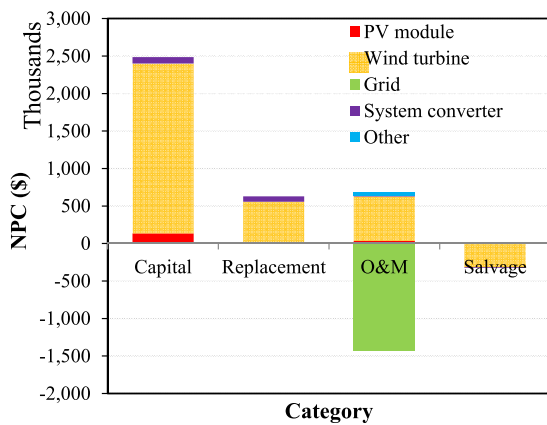
Evidently, there exists a convergence of optimum configuration for each region. Hence, an analysis of electricity production under such conditions is warranted. In the following paragraphs, the production forecast along with the associated cost summary is presented for a few salient regions.

From the analysis above, it is found that Kuakata has high wind potential along with an appreciable amount of solar energy potential. For this reason, wind turbine and solar PV panels are needed for finding the optimum solution in this region. The cost summary for Kuakata region is shown in Figure 15(a) where the individual component costs are given. From this Figure, it can be seen clearly that wind turbine cost is the dominating parameter in the initial capital cost sector while the grid system dominates in the operation & maintenance sector. Figure 15(b) shows the monthly average electricity production from various sources (wind-PV-grid) for a combined renewable fraction of 88% where the major contribution is coming from the wind turbines:

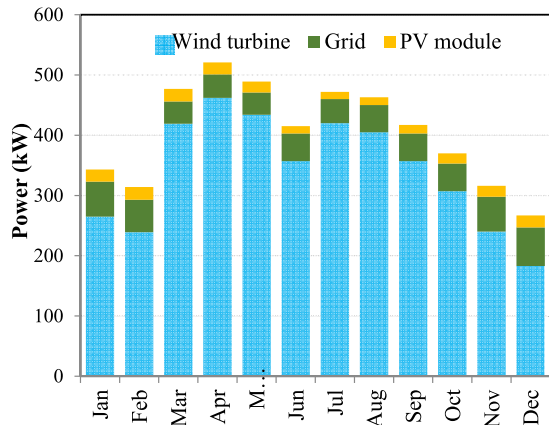
TABLE 5. Feasibility chart for the five locations.

Region	Wind-Grid				PV-Grid				Wind-PV-Grid				Off-Grid
	0.5 MW	1 MW	2 MW	3 MW	0.5 MW	1 MW	2 MW	3 MW	0.5 MW	1 MW	2 MW	3 MW	
Magnama	✓, ☑	✓, ☑	✗, ☑	✗	✗	✗	✗	✗	✗, ☑	✗, ☑	✗	✗	✗
Kuakata	✓, ☑	✓, ☑	✗, ☑	✗	✗	✗	✗	✗	✓, ☑	✓, ☑	✗, ☑	✗	✗
Dinajpur	✗	✗	✗	✗	✓, ☑	✓, ☑	✓, ☑	✗, ☑	✗	✗	✗	✗	✗
Sitakunda	✓, ☑	✓, ☑	✗, ☑	✗	✓, ☑	✓, ☑	✗, ☑	✗	✓, ☑	✓, ☑	✗, ☑	✗	✗
Rangpur	✗	✗	✗	✗	✓, ☑	✓, ☑	✗, ☑	✗	✗	✗	✗	✗	✗

N.B. ✗ infeasible, ✓ feasible for 10% nominal discount rate, ☑ feasible for 9 % nominal discount rate



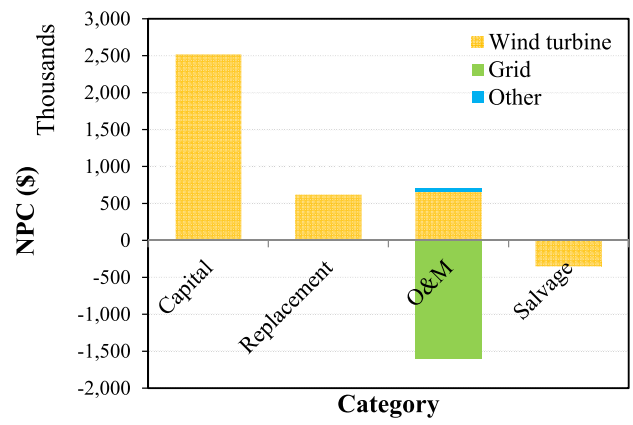
(a)



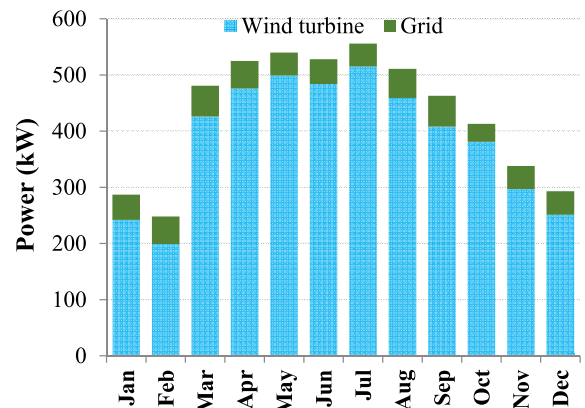
(b)

FIGURE 15. (a) Cost summary (\$) for Kuakata. Wind turbine cost is the dominating parameter in the initial capital cost sector while the grid system dominates in the operation & maintenance sector. (b) Monthly average electricity production for Kuakata (W-PV-G) under the optimum configuration. A combined renewable fraction of 88% is found where the major contribution is coming from the wind turbines (84% renewable energy comes from the wind farm and 4% renewable energy comes from PV cells).

84% renewable energy comes from the wind farm and 4% renewable energy comes from PV cells. An approximate renewable contribution of 94% is observed for Sitakunda.



(a)



(b)

FIGURE 16. (a) Cost summary for Magnama. Capital cost is needed only for wind turbines. However, the maximum operating cost is found for grid components because grid energy purchase cost is considered part of the operation & maintenance cost. (b) Monthly average electric energy production for Magnama considering the optimum configuration and optimum value of R, simultaneously.

The cash flow summary for Magnama is shown in Figure 16(a) where the capital cost is needed only for wind turbines. However, the maximum operating cost is

**TABLE 6.** GHG emission (kg/year) by the proposed models for all five locations.

Location	Existing Grid system			W-G			PV-G			W-PV-G			Off-Grid
	CO <sub>2</sub>	SO <sub>2</sub>	NO <sub>x</sub>	CO <sub>2</sub>	SO <sub>2</sub>	NO <sub>x</sub>	CO <sub>2</sub>	SO <sub>2</sub>	NO <sub>x</sub>	CO <sub>2</sub>	SO <sub>2</sub>	NO <sub>x</sub>	
Magnama	794115	4,029	1,971	215,465	1,093	535	577,783	2,932	1,434	304,139	1,543	755	0
Kuakata	761,605	3,864	1,890	212,222	1,077	527	614,386	3,117	1,525	314,725	1,597	781	0
Dinajpur	529,714	2,688	1,314	253,477	1,286	629	365,465	1,854	907	283,066	1,436	702	0
Sitakunda	350,601	1,779	870	40,959	207	102	343,699	1,744	853	73,537	373	182	0
Rangpur	421,202	2,137	1,045	110,331	560	274	287,499	1,459	713	179,124	909	444	0

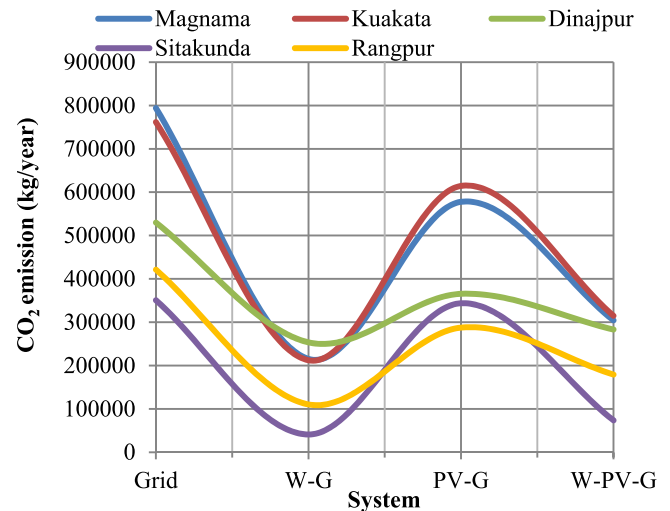
found for grid components because grid energy purchase cost is considered as an operation & maintenance cost of the system. The monthly average energy production under optimum configuration for Magnama (Wind/grid) is presented in Figure 16(b). In this system, solar energy made no contribution; and only the grid and wind contributed to producing energy for meeting the local load demand. Wind turbine contributed 89% and the rest of the energy is supplied by the grid system.

### VIII. ANCILLARY BENEFITS

The crux of our work is based on providing low-cost electricity to people living in rural areas of Bangladesh. However, our propositions carry with them certain concomitant benefits, not least of which is environmental benefits and social benefits. Since practicability alone cannot determine whether the present infrastructure should be overhauled or not, we have to give critical attention to the new things our plan brings to the table. First of all, there has to be an analysis of the GHG gas emissions tradeoff we are achieving. If the tradeoff tips the scale in favor of the grid-only system, that might prove fatal for our feasibility analysis. On the other hand, we should also focus on the benefits accrued on society in response to the implementation of our plans. Both of these issues are given ample analyses below.

#### A. ENVIRONMENTAL BENEFITS

For finding the optimum configuration more accurately for these selected locations, the environmental impact has to be considered. In this paper, annual CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> gas emissions are estimated for evaluating the environmental feasibility of different system configurations. By multiplying the emission factor g/kWh with net grid energy purchase value by the system, emission values are found. Emission factor (g/kWh) for the three major pollutants are 540 g/kWh for CO<sub>2</sub>, 2.74 g/kWh for SO<sub>2</sub> and 1.34 g/kWh for NO<sub>x</sub> [56], [57], [58]. Negative emission will occur if the system sells more energy to the grid than it purchases annually. The yearly numerical value of emission for different models and locations is shown in Table 6. For example, in Magnama region, the emission of CO<sub>2</sub> is found as 794,115 kg per year for the standard grid, 215,465 kg/yr for W-G, 577,783 kg/yr for PV-G and 304,139 kg/yr for W-PV-G. Among these four



**FIGURE 17.** CO<sub>2</sub> emission (kg/year) for four system configurations. It is readily visible that RE based grid-connected hybrid models have high environmental impacts than the standard grid system.

models, W-G configuration is more environmentally viable for Magnama region. Though the off-grid model has no emission, it is not a viable choice. Figure 17 shows the CO<sub>2</sub> emissions (kg/year) for four system configurations in every region. From this Figure, it can be said that RE based grid-connected hybrid models (PV-G, W-G, and PV-W-G) have a high environmental impact than the standard grid system.

From the above analysis, it is evident that PV-G model is environmentally feasible for Dinajpur and Rangpur region; and W-G for Magnama. In all cases, we see a strong negative correlation between adoption of RES and GHG emissions, which substantiate our claim of environmental benefits.

#### B. SOCIAL BENEFITS

The quality of life for a certain community has a positive correlation with the amount of energy it consumes or metabolizes [22]. Effectively, we can track the growth in community well-being by tracking the electricity consumption pattern of that particular society. It may be hard to perceive from the vantage point of an urban lifestyle, but nighttime in villages equates to complete inactivity, owing principally to a lack of illumination. But this situation would change with access to new sources of electricity. Villagers can harvest or keep their







There are lots of aspects that need future academic research works on the prospect of RE in Bangladesh. A key area is the necessary planning and assessments, for example, available infrastructural and monetary resources available for RE in Bangladesh; prospects of using Climate Change Trust Fund for RE development; and ways to increase awareness regarding climate change and RE deployment. There are also the issues that need immediate attention such as ways to mitigate the effect of natural disasters on RE plants; ways to meet the current load demand in Bangladesh; ways to provide electricity in remote areas; optimum power plant operation and commissioning after the demand has been met. Moreover, feasibility of RE sources other than PV and wind, such as tidal energy; control systems to integrate RE to the grid system of Bangladesh; feasibility of deploying energy storages for energy stability; necessity and scope of accurate forecasting of RE generation; tariff framework for RE consumption, grid supply from load-side generation (e.g. grid-connected solar panels on the rooftop of an end-consumer); and mathematical modeling of the systems – all demand equal attention to steer the nation towards a sustainable green energy system.

## APPENDIX

See Tables 7 and 8.

## REFERENCES

- [1] H. Rezzouk and A. Mellit, "Feasibility study and sensitivity analysis of a stand-alone photovoltaic–diesel–battery hybrid energy system in the north of Algeria," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 1134–1150, Mar. 2015. doi: 10.1016/j.rser.2014.11.103.
- [2] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 609–620, Sep. 2016. doi: 10.1016/j.rser.2016.05.039.
- [3] W. D. Kellogg, M. H. Nehrir, G. Venkataramanan, and V. Gerez, "Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems," *IEEE Trans. Energy Convers.*, vol. 13, no. 1, pp. 70–75, Mar. 1998. doi: 10.1109/60.658206.
- [4] S. M. Shaahid and I. El-Amin, "Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development," *Renew. Sustain. Energy Rev.*, vol. 13, no. 3, pp. 625–633, 2009. doi: 10.1016/j.rser.2007.11.017.
- [5] A. Khelif, A. Talha, M. Belhamel, and A. H. Arab, "Feasibility study of hybrid diesel–PV power plants in the southern of Algeria: Case study on AFRA power plant," *Int. J. Elect. Power Energy Syst.*, vol. 43, no. 1, pp. 546–553, Dec. 2012. doi: 10.1016/j.ijepes.2012.06.053.
- [6] N. Agarwal, A. Kumar, and Varun, "Optimization of grid independent hybrid PV–diesel–battery system for power generation in remote villages of Uttar Pradesh, India," *Energy Sustain. Develop.*, vol. 17, no. 3, pp. 210–219, 2013. doi: 10.1016/j.esd.2013.02.002.
- [7] J. Dekker, M. Nthontho, S. Chowdhury, and S. P. Chowdhury, "Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa," *Int. J. Elect. Power Energy Syst.*, vol. 40, no. 1, pp. 104–112, 2012. doi: 10.1016/j.ijepes.2012.02.010.
- [8] N. E. Mbakaa, N. J. Mucho, and K. Godpromesse, "Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon," *Renew. Energy*, vol. 35, no. 10, pp. 2391–2398, 2010. doi: 10.1016/j.renene.2010.03.005.
- [9] A. B. Kanase-Patil, R. P. Saini, and M. P. Sharma, "Integrated renewable energy systems for off grid rural electrification of remote area," *Renew. Energy*, vol. 35, no. 6, pp. 1342–1349, 2010. doi: 10.1016/j.renene.2009.10.005.
- [10] A. N. Celik, "Optimisation and techno-economic analysis of autonomous photovoltaic–wind hybrid energy systems in comparison to single photovoltaic and wind systems," *Energy Convers. Manage.*, vol. 43, no. 18, pp. 2453–2468, 2002. doi: 10.1016/S0196-8904(01)00198-4.
- [11] F. A. Shifa and M. F. U. Butt, "A feasibility study for deployment of wind energy based power production solution in Islamabad, Pakistan," in *Proc. Int. Conf. Emerg. Technol.*, Oct. 2012, pp. 1–6. doi: 10.1109/ICET.2012.6375500.
- [12] S. K. Pawar, Y. V. Aaher, A. C. Chaudhari, and Y. B. Jadhav, "Modeling and simulation of hybrid solar-wind-grid power generation system for electrification," in *Proc. Int. Conf. Adv. Eng. Technol. (ICAET)*, May 2014, pp. 1–6. doi: 10.1109/ICAET.2014.7105291.
- [13] T. M. Tawfik, M. A. Badr, E. Y. El-Kady, and O. E. Abdellatif, "Optimization and energy management of hybrid standalone energy system: A case study," *Renew. Energy Focus*, vol. 25, pp. 48–56, Jun. 2018. doi: 10.1016/j.ref.2018.03.004.
- [14] N. Zhou, N. Liu, J. Zhang, and J. Lei, "Multi-objective optimal sizing for battery storage of PV-based microgrid with demand response," *Energies*, vol. 9, no. 8, p. 591, 2016. doi: 10.3390/en9080591.
- [15] Investment Plan for Bangladesh, Power Division, Ministry of Power, Energy & Mineral Resources. (2015). *Scaling Up Renewable Energy in Low-Income Countries (SREP)*. [Online]. Available: [https://www.climateinvestmentfunds.org/sites/cif\\_enc/files/bangladesh\\_srep\\_ip\\_final.pdf](https://www.climateinvestmentfunds.org/sites/cif_enc/files/bangladesh_srep_ip_final.pdf)
- [16] BPDB. *Annual Report 2011-2012 to 2017-2018*. Accessed: Aug. 2, 2019. [Online]. Available: [http://www.bpdb.gov.bd/bpdb\\_new/resourcefile/annualreports/](http://www.bpdb.gov.bd/bpdb_new/resourcefile/annualreports/)
- [17] A. H. Baky, M. Rahman, and A. K. M. S. Islam, "Development of renewable energy sector in Bangladesh: Current status and future potentials," *Renew. Sustain. Energy Rev.*, vol. 73, pp. 1184–1197, Jun. 2017. doi: 10.1016/j.rser.2017.02.047.
- [18] SREDA. *Annual Report 2017-2018*. Accessed: Aug. 2, 2019. [Online]. Available: [http://www.sreda.gov.bd/d3pbs\\_uploads/files/Annual%20Report%202017-2018.pdf](http://www.sreda.gov.bd/d3pbs_uploads/files/Annual%20Report%202017-2018.pdf)
- [19] T. Islam, S. A. Shahir, T. M. I. Uddin, and A. Z. A. Saifullah, "Current energy scenario and future prospect of renewable energy in Bangladesh," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 1074–1088, Nov. 2014. doi: 10.1016/j.rser.2014.07.149.
- [20] P. K. Halder, N. Paul, M. U. H. Joardder, and M. Sarker, "Energy scarcity and potential of renewable energy in Bangladesh," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 1636–1649, Nov. 2015. doi: 10.1016/j.rser.2015.07.069.
- [21] IDCOL. *Design of Small Solar Home System (SSHS)*. Accessed: Aug. 16, 2019. [Online]. Available: <http://www.idcol.org>
- [22] B. K. Das, N. Hoque, S. Mandal, T. K. Pal, and A. Raihan, "A techno-economic feasibility of a stand-alone hybrid power generation for remote area application in Bangladesh," *Energy*, vol. 134, pp. 775–788, Sep. 2017. doi: 10.1016/j.energy.2017.06.024.
- [23] B. Ozerdem, S. Ozer, and M. Tosun, "Feasibility study of wind farms: A case study for Izmir, Turkey," *J. Wind Eng. Ind. Aerodyn.*, vol. 94, no. 10, pp. 725–743, 2006. doi: 10.1016/j.jweia.2006.02.004.
- [24] (2018). *Weather Online Report of Cox's Bazar*. [Online]. Available: <https://www.weatheronline.co.uk/weather/maps/forecastmaps>
- [25] M. Nurunnabi, N. K. Roy, and M. A. Mahmud, "Investigating the environmental and socio-economic impacts of grid-tied photovoltaic and on-shore wind systems in Bangladesh," *IET Renew. Power Gener.*, vol. 12, no. 9, pp. 1082–1090, Jul. 2018. doi: 10.1049/iet-rpg.2017.0751.
- [26] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renew. Energy*, vol. 45, pp. 7–15, Sep. 2012. doi: 10.1016/j.renene.2012.01.087.
- [27] K. Y. Lau, M. F. M. Yousof, S. N. M. Arshad, M. Anwari, and A. H. M. Yatim, "Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions," *Energy*, vol. 35, no. 8, pp. 3245–3255, Aug. 2010. doi: 10.1016/j.energy.2010.04.008.
- [28] P. M. Murphy, S. Twaha, and I. S. Murphy, "Analysis of the cost of reliable electricity: A new method for analyzing grid connected solar, diesel and hybrid distributed electricity systems considering an unreliable electric grid, with examples in Uganda," *Energy*, vol. 66, pp. 523–534, Mar. 2014. doi: 10.1016/j.energy.2014.01.020.
- [29] M. A. M. Ramli, A. Hiendro, K. Sedraoui, and S. Twaha, "Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia," *Renew. Energy*, vol. 75, pp. 489–495, Mar. 2015. doi: 10.1016/j.renene.2014.10.028.
- [30] G. M. Shafiullah, M. T. O. Amanullah, A. B. M. S. Ali, D. Jarvis, and P. Wolfs, "Prospects of renewable energy—A feasibility study in the Australian context," *Renew. Energy*, vol. 39, no. 1, pp. 183–197, 2012. doi: 10.1016/j.renene.2011.08.016.
- [31] HOMER *Analysis of Micropower System Options*. Accessed: Oct. 20, 2017. [Online]. Available: <https://analysis.nrel.gov/homer/>

- [32] M. A. Shoeb and G. M. Shafiullah, "Renewable energy integrated islanded microgrid for sustainable irrigation—A Bangladesh perspective," *Energies*, vol. 11, no. 5, p. 1283, 2018. doi: [10.3390/en11051283](https://doi.org/10.3390/en11051283).
- [33] M. M. Rahman, S. Hettiwatte, G. M. Shafiullah, and A. Arefi, "An analysis of the time of use electricity price in the residential sector of Bangladesh," *Energy Strategy Rev.*, vol. 18, pp. 183–198, Dec. 2017. doi: [10.1016/j.esr.2017.09.017](https://doi.org/10.1016/j.esr.2017.09.017).
- [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](https://doi.org/10.1016/j.enpol.2009.04.039).
- [35] S. A. Chowdhury, S. Aziz, S. Groh, H. Kirchhoff, and W. L. Filho, "Off-grid rural area electrification through solar-diesel hybrid minigrids in Bangladesh: Resource-efficient design principles in practice," *J. Cleaner Prod.*, vol. 95, pp. 194–202, May 2015. doi: [10.1016/j.jclepro.2015.02.062](https://doi.org/10.1016/j.jclepro.2015.02.062).
- [36] F. Ahmed, C. Trimble, and N. Yoshida, "The transition from underpricing residential electricity in Bangladesh: Fiscal and distributional impacts," World Bank, World Bank Rep. 76441-BD, 2013.
- [37] P. Perera and J. S. Bayley, "Sector assistance program evaluation for Bangladesh energy sector," Dept. Asian Develop. Bank-Independ. Eval., Metro Manila, Philippines, Eval. Study Rep., Project no. SAP:BAN 2009-36, 2009.
- [38] ESMAP, Washington, DC, USA, World Bank. (2017). *Mini-Grids in Bangladesh: A Case Study of An Incipient Market*. [Online]. Available: <http://documents.worldbank.org/curated/en/669331512390210193/Mini-grids-in-Bangladesh-a-case-study-of-an-incipient-market>
- [39] S. K. Nandi and H. R. Ghosh, "Prospect of wind–PV–battery hybrid power system as an alternative to grid extension in Bangladesh," *Energy*, vol. 35, no. 7, pp. 3040–3047, 2010. doi: [10.1016/j.energy.2010.03.044](https://doi.org/10.1016/j.energy.2010.03.044).
- [40] Z. Collen, "A study into the techno-economic feasibility of photovoltaic and wind generated electricity for enhancement of sustainable livelihoods on Likoma Island in Malawi," Ph.D. dissertation, Dept. Mech., Elect. Manuf. Eng., Loughborough Univ., Loughborough, U.K., 2015. Accessed: Nov. 28, 2016. [Online]. Available: <https://dspace.lboro.ac.uk/2134/16630>
- [41] A. Esfandyari, B. Norton, M. Conlon, and S. J. McCormack, "Performance of a campus photovoltaic electric vehicle charging station in a temperate climate," *Solar Energy*, vol. 177, pp. 762–771, Jan. 2019. doi: [10.1016/j.solener.2018.12.005](https://doi.org/10.1016/j.solener.2018.12.005).
- [42] G. J. Dalton, D. A. Lockington, and T. E. Baldock, "Case study feasibility analysis of renewable energy supply options for small to medium-sized tourist accommodations," *Renew. Energy*, vol. 34, pp. 1134–1144, Apr. 2009. doi: [10.1016/j.renene.2008.06.018](https://doi.org/10.1016/j.renene.2008.06.018).
- [43] M. Nurunnabi, "Design and analysis of grid-connected hybrid power systems based on renewable energy: Bangladesh perspective," M.S. thesis, Khulna Univ. Eng. Technol., Khulna, Bangladesh, 2016. [Online]. Available: <http://dspace.kuet.ac.bd/handle/20.500.12228/98>
- [44] *DESCO Appliances Calculator*. Accessed: Jan. 2, 2019. [Online]. Available: <https://www.desco.org.bd/?page=bill-calculator>
- [45] REB, Annual Report 2017–2018. Accessed: Jan. 2, 2019. [Online]. Available: [http://reb.portal.gov.bd/sites/default/files/files/reb.portal.gov.bd/page/8596cfe6\\_8cde\\_4643\\_acb1\\_68cd973e413c/AnnualReport\\_2017-18\\_Part\\_1.pdf](http://reb.portal.gov.bd/sites/default/files/files/reb.portal.gov.bd/page/8596cfe6_8cde_4643_acb1_68cd973e413c/AnnualReport_2017-18_Part_1.pdf)
- [46] *Patuakhali Rural Electrification Board*. Accessed: Jan. 2, 2019. [Online]. Available: <http://pbs.patuakhali.gov.bd/>
- [47] NASA. (2017). *Surface Meteorology and Solar Energy (SSE) Database*. [Online]. Available: <https://power.larc.nasa.gov/>
- [48] N. Farha, M. Nur-Ul-Safa, B. D. Rahamatullah, and M. S. Ali, "Prospects of wind energy in the coastal region of Bangladesh," *Int. J. Sci. Eng. Res.*, vol. 3, pp. 1–5, Aug. 2012.
- [49] X. Fu, S. Li, M. Fairbank, D. C. Wunsch, and E. Alonso, "Training recurrent neural networks with the Levenberg–Marquardt algorithm for optimal control of a grid-connected converter," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 26, no. 9, pp. 1900–1912, Sep. 2015. doi: [10.1109/TNNLS.2014.2361267](https://doi.org/10.1109/TNNLS.2014.2361267).
- [50] *Solar Panels*. Accessed: Nov. 22, 2017. [Online]. Available: <https://www.solarlandusa.com/>
- [51] (2016). *Kingspan KW6 Wind Turbine*. [Online]. Available: <https://photonenergy.co.uk/images/products/wind/kingspan/Kingspan%20KW6%20Wind%20Turbine%20Noise%20Performance%20Test%20B2.pdf>
- [52] International Renewable Energy Agency. *Wind Power. Renewable Energy Technologies: Cost Analysis Series*. [Online]. Available: [https://www.irena.org/documentdownloads/publications/re\\_technologies\\_cost\\_analysis-wind\\_power.pdf](https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf)
- [53] *Manufacturer Datasheet: Sanyo HIP-200BA19 (200W) Solar Panel*, Panasonic, Kadoma, Japan, 2017.
- [54] *PMSG Wind Turbine Datasheet*. Accessed: Aug. 2, 2019. [Online]. Available: <http://www.chinahammer.cn/index.php/index/content/164>
- [55] C. Zalengera, "A study into the techno-economic feasibility of photovoltaic and wind generated electricity for enhancement of sustainable livelihoods on Likoma Island in Malawi," Ph.D. dissertation, Loughborough Univ., Loughborough, U.K., 2015. Accessed: Aug. 2, 2019. [Online]. Available: <https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.634785>
- [56] S. Grover, "Energy, Economic and environmental benefits of the solar America initiative," ECONorthwest, Portland, OR, USA, Subcontract Rep. NREL/SR-640-41998, 2007. [Online]. Available: <https://www.nrel.gov/docs/fy07osti/41998.pdf>
- [57] M. M. Rahman. *Bangladesh National Conservation Strategy Report*. Accessed: Nov. 28, 2017. [https://files/bforest.portal.gov.bd/notices/c3379d22\\_ee62\\_4dec\\_9e61029\\_75171074d885/19.%20Power\\_NCS.pdf](https://files/bforest.portal.gov.bd/notices/c3379d22_ee62_4dec_9e61029_75171074d885/19.%20Power_NCS.pdf)
- [58] M. Nurunnabi, N. K. Roy, and H. R. Pota, "Optimal sizing of grid-tied hybrid renewable energy systems considering inverter to PV ratio—A case study," *J. Renew. Sustain. Energy*, vol. 11, Jan. 2019, Art. no. 013505. doi: [10.1063/1.5052492](https://doi.org/10.1063/1.5052492).
- [59] Pun. *Bringing Internet to Nepal's Remote, Mountainous Villages*. Accessed: Jun. 2, 2017. [Online]. Available: <https://www.internetsociety.org/blog/2017/06/bringing-internet-nepals-remote-mountainous-villages/>
- [60] K. Yoo, E. Park, H. Kim, J. Y. Ohm, T. Yang, K. J. Kim, H. J. Chang, and A. P. del Pobal, "Optimized renewable and sustainable electricity generation systems for Ulleungdo Island in South Korea," *Sustainability*, vol. 6, no. 11, pp. 7883–7893, 2014. doi: [10.3390/su6117883](https://doi.org/10.3390/su6117883).
- [61] Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Resource assessment and techno-economic analysis of a grid-connected solar PV-wind hybrid system for different locations in Saudi Arabia," *Sustainability*, vol. 10, no. 10, p. 3690, 2018. doi: [10.3390/su10103690](https://doi.org/10.3390/su10103690).



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