Design Optimization and Sensitivity Analysis of Hybrid Renewable Energy Systems: A case of Saint Martin Island in Bangladesh

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Abstract-This paper presents the design optimization and sensitivity analysis of the hybrid renewable energy system (HRES) for Saint Martin island in Bangladesh. An optimization software named Hybrid Optimization Model for Electric Renewable (HOMER) is used to find out the best technically viable and cost-effective renewable stand-alone model. The Saint Martin island has enormous potential to utilize the solar Photovoltaic (PV) and wind energy. The study considers six cases with various energy sources including solar PV, wind energy, and diesel generator. Each case is simulated and optimized using HOMER. The results demonstrate that PV-wind-diesel generator (hybrid) delivers the best optimal design for Saint Martin island in terms of cost of energy (COE) followed by PV-Diesel Generator, Wind-PV and Wind alone and PV alone system. In addition, the results are compared with other hybrid systems in order to check our data validity. Moreover, the impact of solar radiation and wind speed on diesel price are identified by carrying out the sensitivity analysis.

Keywords- HOMER, Cost of Energy (COE), Net Present Cost (NPC), Saint Martin Island, Optimization, sensitivity analysis

1. Introduction

In the recent decades, energy has become a basic necessity for the human life. The role of energy in building up this modern civilization cannot be determined. Fossil energy has played a vital role to fulfill the energy requirement of earth. In view of current stores and utilization rate of fossil assets, the world will manage 122 years for coal, 42 years for oil, 60 years for natural gas [1]. Globally, there will be a 36% increase in fossil fuel energy consumption between the year 2011 and 2030 if the annual consumption rate is 1.6% [2]. However, a degradation of fossil fuels reserve has been observed worldwide over the last few decades. Moreover, the consumption rate of fossil fuels has been rising significantly compared to the limited reservation. Globally, there is a 13.5% increase in fossil-based power generation while the non-fossil sources have declined by 10.8% between the year 1990 and 2010 [3]. Therefore, the world is facing some serious consequences such as global warming and CO_2 emissions [4]. Due to the environmental pollution and resource degradation of fossil fuels, the introduction of alternative energy sources has obtained massive attention to meet the present energy demand.

Energy plays a significant role in the economic and social development of Bangladesh. However, accessibility of electricity cannot be delivered in a continuous, affordable and reliable way. The county has achieved only 62% access to electricity (including renewable energy) and generation of electricity per capita is only 321 KWh [5], [6]. There are many locations in Bangladesh, especially in remote island like Saint-Martin island, which have no access to a reliable power supply. Providing energy to remote areas/islands in a sustainable way is a basic requirement nowadays due to depletion of fossil fuel reserve, fuel cost escalation associated with conventional energy generation, population growth, and insufficient waste disposal facilities. Furthermore, due to the international awareness on global warming and the shortage of supply of natural gas and oil, the renewable energy based power plants have become promising alternatives and has been growing rapidly. The government of Bangladesh are investing significantly in renewable energy and has introduced renewable energy policy with an aim of implementing renewable energy based power plants to achieve 10% of the total power demand by 2020 [7]. Photovoltaic solar and wind generation units are the most attractive choices for delivering electricity to rural and remote areas and islands where utility lines are expensive to introduce because of the landscape [8].

Renewable energy resources have gained huge attention and become appropriate alternatives for fossil fuel resources [9]. Nevertheless, renewable energy has shortcomings in terms of high capital cost and irregular supply [10]. Therefore, a new strategy namely HRES is implemented to address these challenges [11]–[15]. HRES can be operated either in on-grid mode and off-grid mode that includes various renewable energy sources and energy storage systems. HRES has become a popular choice for supplying electricity in rural and remote areas. Due to the intermitted supply as well as the lack of capacity of renewable sources, energy storage system can be added as backup sources in order to provide the reliable and continuous supply of electricity. On the contrary, when excess generation is produced by renewable sources, the additional power can be either stored in energy storages or can transmit to the utility grid. HRES provides some benefits such as it reduces COE, decreases CO_2 emission, and supplies safe and affordable electricity in remote, rural areas as well as islands [16]. All the merits meet the requirement of Sustainable Development (SD) in terms of social, economic and the environment.

In this paper, a hybrid system including wind energy, solar PV, and the diesel generator is proposed to find out the optimal size of HRES's equipment at Saint Martin island in Bangladesh. Since the sunlight is not accessible during night and wind speed is changing for the duration of the day, a diesel generator can be introduced to avoid discontinuous supply of power. To achieve the objectives, a powerful software tool, named HOMER, is used to discover the best design of HRES for the Saint Martin island.

The rest of the paper is arranged as follows. First, methodology part outlines the overall methodological framework. Second, explanation of HOMER software and selection of study area are presented. Third, the potential of solar PV and wind energy are explored in Saint Martin island. Fourth, the procedures of data collection methods with load profile and data inputs are discusssed. Fifth, the different structures of renewable energy hybrid power supply are shown. Sixth, the optimization results are presented and then compared with other literature. Finally, the paper concludes with sensitivity analysis.

2. Methodology

A methodological framework helps to achieve the objectives of this study, as shown in Fig. 1.

3. HOMER Software Description

There is various software which is used for achieving optimal sizing of HRES. Among them, HOMER software has attained massive popularity which is developed by National Renewable Energy Laboratory (NREL), United States [17]. Many resources are included in HOMER such as solar PV, wind turbine, biomass, various energy storage devices and converter. The software requires technical specifications on energy sources, energy storage and control strategies. The software also needs some input parameters such as capital and replacement cost, type of component, efficiency and life cycle [18]. Figure 2 illustrates an architecture of HOMER software [19][20].

4. Study Area

Saint Martin is the only coral island in Bangladesh which is located in the southern bay and about 500 kilometers away from the capital Dhaka and 10 kilometers away from the mainland [21].

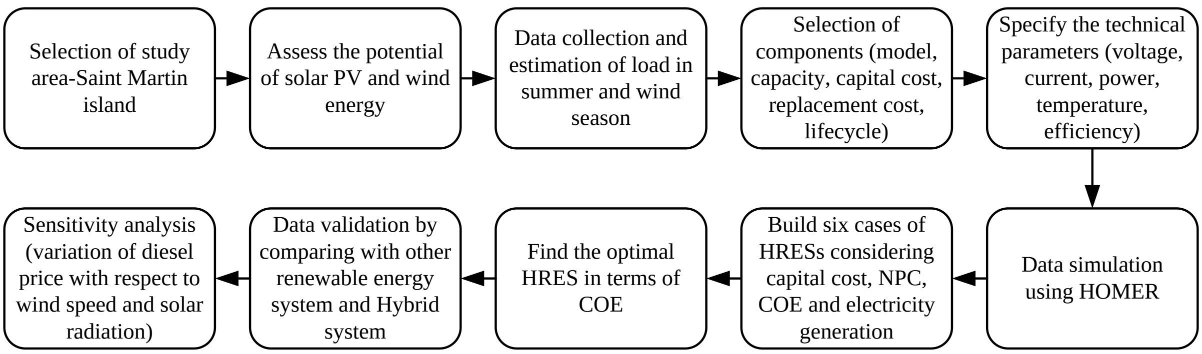

Fig. 1. The overall methodological framework of the study

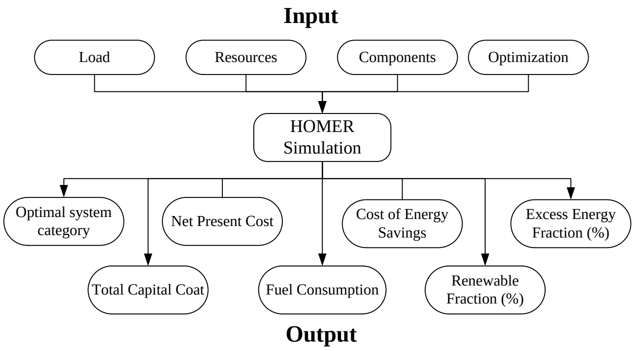

Fig. 2. Architecture of HOMER software

Saint Martin Island is the most excellent vacationer island in Bangladesh. There are nearly 8,000 people live on this small island with an area of 12 square-kilometer [22]. Around 3,000 people visit this island daily during the month of November-February, which exceeds the holding capacity of this small island [22].The inhabitants of the island use stand-alone diesel generators to meet their power demand. However, they are not functioning admirably and are not sufficient enough to meet the requirement. Besides, they use diesel, kerosene, and wood to light their house [23]. The electric grid is not possible to implement due to geographical conditions and it will not be economically feasible. Solar energy and wind energy could be the promising alternatives to meet the electricity demand.

5. Renewable Energy potential in Saint Martin Island

5.1. Solar energy potential

The latitude and longitude of the study area are 20.60° degrees north and 92.32° east respectively. Geographically,

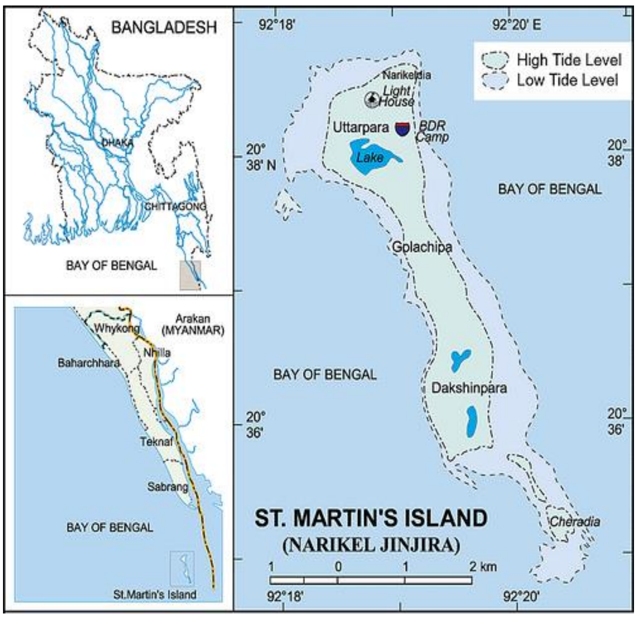

Fig. 3. Saint Martin Island on the map

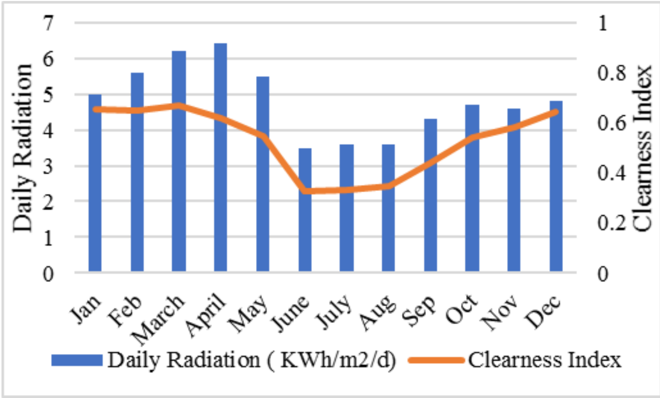

Fig. 4. Solar radiation data in Saint Martin island in a year

the location is placed in a favorable position for achieving the maximum utilization of solar energy [24]. The solar radiates power at 100-300 W/m² per annum [25]. The radiation reaches its highest value in March-April and lowest in December-January. As hourly data is unavailable in Saint Martin, in this circumstance, National Aeronautics and Space Administration (NASA) website is used for achieving monthly average global radiation data [26]. Fig. 4 indicates that high radiation of solar energy is available between February and April. The average annual clearness index displays an average value of 0.51 with daily mean radiation of 4.8 kWh/m²/day.

5.2 Wind energy potential

Bangladesh has a 724-kilometer long coastal line along the Bay of Bengal. Moreover, there lies some island in the bay of bengal where wind speed is sufficiently high to generate electricity. The monthly average wind speed in the coastal area of Bangladesh varies from 3m/s to 9m/s at different heights [27] [28]. The highest wind speed is observed in June and July. Wind speed keeps steady during the rest of the time of year. Usually, wind velocity at the coastal areas and isolated islands are quite higher than rest of the locations. Figure 5 presents the average wind speed of Saint Martin in a month. Wind power curve is shown in Figure 6.

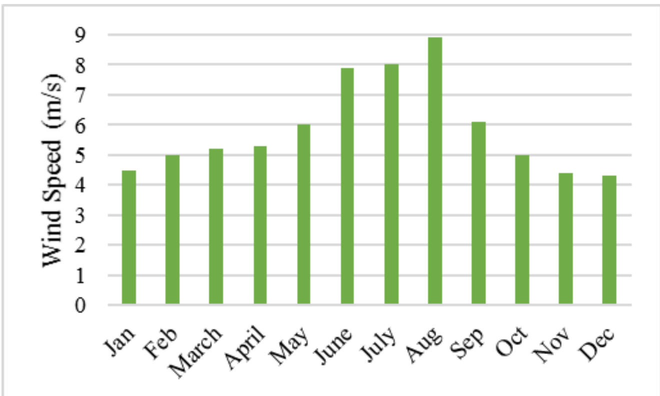

Fig. 5. Monthly average wind speed in Saint Martin Island

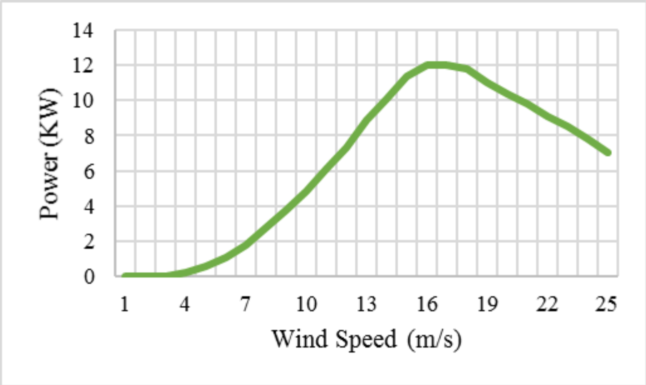

Fig.6. Wind power curve of BWC Excel–S wind turbine

6. Data Collection and Electric load Profile

Information related to energy demand in Saint Martin island were collected in the month of November and December 2015. Additionally, a meeting was held with informants as well as with different stakeholders in order to get a comprehensive knowledge about energy access in Saint Martin island.Both standardized surveys and checklist based questionnaire were used to assess the capacity of various appliances, their usage patterns, and electricity demand. The demand is estimated distinctly for two different seasons for households, shops, restaurants, and hotels. The summer stays from March to October while the winter starts in November and continues until February. A total of 50 houses, 15 shops, 5 restaurants, 5 hotels are selected randomly for the estimation of demand. Table 1 depicts the information of estimated load requirement for summer and winter season and Fig. 7 and Fig. 8 show average daily load profile of summer and winter season.

7. Data description

7.1 Solar data

The capital cost of the solar panel is USD 350. The replacement cost is assumed at the same as the capital cost. The Operation and maintenance (O & M) cost is considered as USD 100/year. O & M costs include testing voltage/current through PV modules and wires, checking connections of wires, inspecting components for moisture, setting on the inverter.

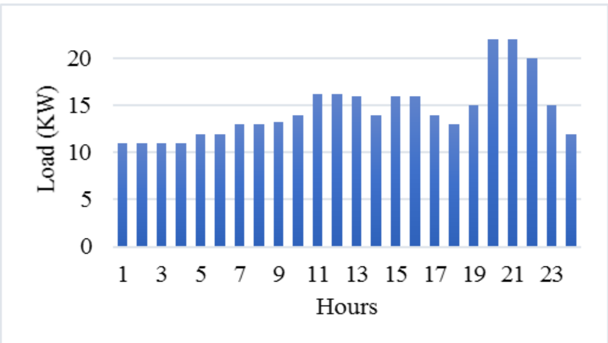

Fig. 7. Average daily load profile of Summer (March to October)

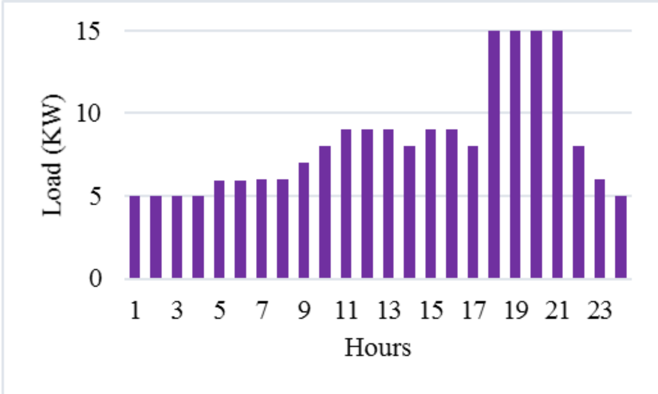

Fig. 8. Average daily load profile of Winter (November to February)

7.2 Generator data

The capital cost of diesel generator is USD 900 with a capacity of 1 kW. The generator can operate upto 15,000 hours which is the lifetime operating hours. The replacement cost is assumed equal to capita cost. The O & M cost is fixed at USD0.04/hour. The fuel price is USD 0.87/liter.

7.3 Battery data

The study has selected Visions 6FM200D as battery model which has the capital cost of USD 1000 with the replacement cost of USD 1000. The O & M cost is USD 50/year. Here, a series connection of 3 batteries is considered as a string.

Accurate estimation of battery states not only helps to provide information about the current and remaining performance of the battery but also gives assurance of a reliable and safe operation of the electric vehicle. The most classical method to estimate SOC is current integration, which expresses the ratio of the available current capacity to the nominal capacity [29] which is shown in Eq. (1).

$$SOC = 1 - \frac{\int i\eta dt}{C_n} \quad (1)$$

Where i is the battery current; C_n is the nominal capacity; t is time and η is the coulombic efficiency defined as the ratio of energy require for charging to the discharging energy needed to regain the original capacity.

7.4 Wind data

This study has chosen a revised version of the Bergey wind power BWC Excel-Style model as the wind turbine. The turbine has the rated the power of 10 kW DC. In addition, lifetime of the turbine is 20 years. The hub height is 25 meters. The investment cost is USD 40,000 with the substitution cost is considered as the same price as capital cost. The O & M cost is USD 130/year. Technical data of wind turbine is shown in Table 2.

Table 1. Estimated electricity demand for Saint Martin Island

				Summer		Winter	
S/N	Description	Number in use	Power (W)	hours/day	Watt-hours/day	hours/day	Watt-hours/day
1	***House***						
	a. CFL	1	20	6	120	8	160
	b. Celling fan	1	75	12	900	0	0
	c.TV	1	200	8	1600	7	1400
	Total (for one house)		295		2620		1560
A	**Total load house**	**50**	**14750**		**131000**		**78000**
2	***Shop***						
	a. CFL	2	20	5	200	7	280
	b. Celling fan	1	75	7	525	0	0
	Total (for one shop)		95		725		280
B	**Total Shops**	**15**	**1425**		**10875**		**4200**
3	***Restaurants***						
	a. CFL	15	20	7	2100	8	2400
	b.Celling fan	8	75	8	4800	0	0
	c.TV	1	200	7	1400	6	1200
	d.Refrigerator	1	250	6	1500	4	1000
	Total (for one restaurant)		545		9800		4600
C	**Total Restaurants**	**5**	**2725**		**49000**		**23000**
4	***Hotel***						
	a. CFL	60	20	6	7200	8	9600
	b.Celling fan	30	75	10	22500	0	0
	c.TV	20	200	5	20000	5	20000
	d.Refrigerator	2	250	12	6000	8	4000
	e.Water pump	1	2000	2	4000	2	4000
	Total (for one hotel)		2545		59700		37600
D	**Total hotels**	**5**	**12725**		**298500**		**188000**
	Total Load (A+B+C+D)		**31625**		**489375**		**293200**

Table 2. Technical data of BWC Excel-S wind turbine [30]

Parameters	Unit	Value
Rotor diameter	meter	7
Number of rotor blades	No.	3
Cut-in wind speed	m/s	2.5
Cut-out wind speed		None
Rated power	kW	10
Capital cost	USD	40000
Replacement cost	USD	40000
Operating and maintenance cost	USD	130/year
Lifetime	years	20 years

7.5 Converter data

A capacity of 1 kW converter is used for DC/AC or AC/DC conversion. USD 518 is fixed as the capital cost of the converter. The value of replacement cost is the same as capital cost. The O & M cost is USD 50/year. The converter has 15 years' lifetime and 90% efficiency. HOMER software input data is shown in Table 3.

7.6 Technical parameters details

Different type of technical parameters is automatically considered in simulation process of HOMER.

8. Systems design

The study has considered six cases with different parameters. The detailed specification of each component along with load requirement is presented in Fig. 9.

9. Optimization Results

HOMER performs simulations and optimization based on specifications to identify the best combination design which delivers the best performance in terms of cost and technical aspects. Table 5 demonstrates the detailed about the size of various components and cost of six cases including capital cost, operating cost, NPC, COE. To meet the load demand in Saint Martin island, the case 1 is designed based on wind turbine and diesel generator alone and simulation is performed using HOMER. In the simulation, the NPC is calculated as USD 2,222,811 with operating cost as USD 37,237 and COE as USD 1.45/kWh. The simulation process performed by HOME for the case 2 shows that the NPC is USD461781, operating cost is USD 217,605/year and COE is USD 0.36/kWh. The NPC for case-3 is estimated as USD 729,598, operating cost as USD 110,778 and COE as USD 0.5/kWh. In case-4, the HOMER calculates COE as USD 0.817/kWh which is higher than PV-Diesel Generator system. The NPC is calculated as USD 593,963 with operating cost as USD 391,107.

Table 3. HOMER software input data

Characteristic	Model	Power	Purchase Cost (USD)*	Replacement Cost (USD)*	O & M Cost (USD)*	Life Time
PV panel	PV-MF100EC4	1 kW	350	350	100/year	20 years
Diesel Generator	Walton Zet10000	1 kW	900	900	0.04/hour	1500 hours
Battery	Vision 6FM200D	2.4 kWh	1000	1000	50/year	4 years
Converter	POWERTECH STD1000W	1 kW	518	518	50/year	15 years
Wind turbine	BWC XLS	10 kW	40000	40000	130/year	20 years

*The price considered are an interpolation of data (quotations) obtain from local Bangladesh manufacturers, distributors, and previously published literature.

9.1 Electricity Production

The total electricity production (MWh/year) and the excess electricity (%) generation for each of the six cases are shown in Table 6. When the generation of electricity is higher than the demand and the batteries do not have the capacity to store the excess electricity is known as excess electricity generation. Among the six cases, case 6 generates the lowest excess electricity while the case 1 produces the highest excess electricity. The main reason for producing excess electricity due to the high value of solar radiation and wind velocity. In case 6, a very small amount of electricity is produced by diesel generator while the PV and wind turbine produce 43% and 56% of electricity respectively. For the other five systems, all components contribute to generate electricity but with different proportion. We know, renewable energy depends on whether condition. Thus, in the case of unstable weather condition, case 3-5 might be incapable of delivering continuous electricity supply to load. As the hybrid system generates excess electricity, this electricity can be either stored into the battery or can be utilized during bad weather condition. As a result, continuous supply of electricity can be provided throughout a year without causing any trouble.

Table 4. Technical parameters used for HOMER

Components	Parameters	Value	Unit
PV	Derating Factor	80	%
	Tracking	No	-
	Slope	20.98	Degree
	Ground reflectance	20	%
	Effect of temperature	20	Degree
Wind	Hub height	25	m
	Blade	2	No.
Battery	Nominal voltage	12	V
	Nominal capacity	200	Ah
	Lifetime Throughout	917	kWh
	Round trip efficiency	80	%
	Initial state of charge	100	%
	Batteries per string	3	-
Generator	Life time	15000	hours
Inverter	Efficiency	85	%
Load	Average	299	kWh/day
	Average	12.5	kW
	Peak	38.8	kW
	Day to day variability	15	%

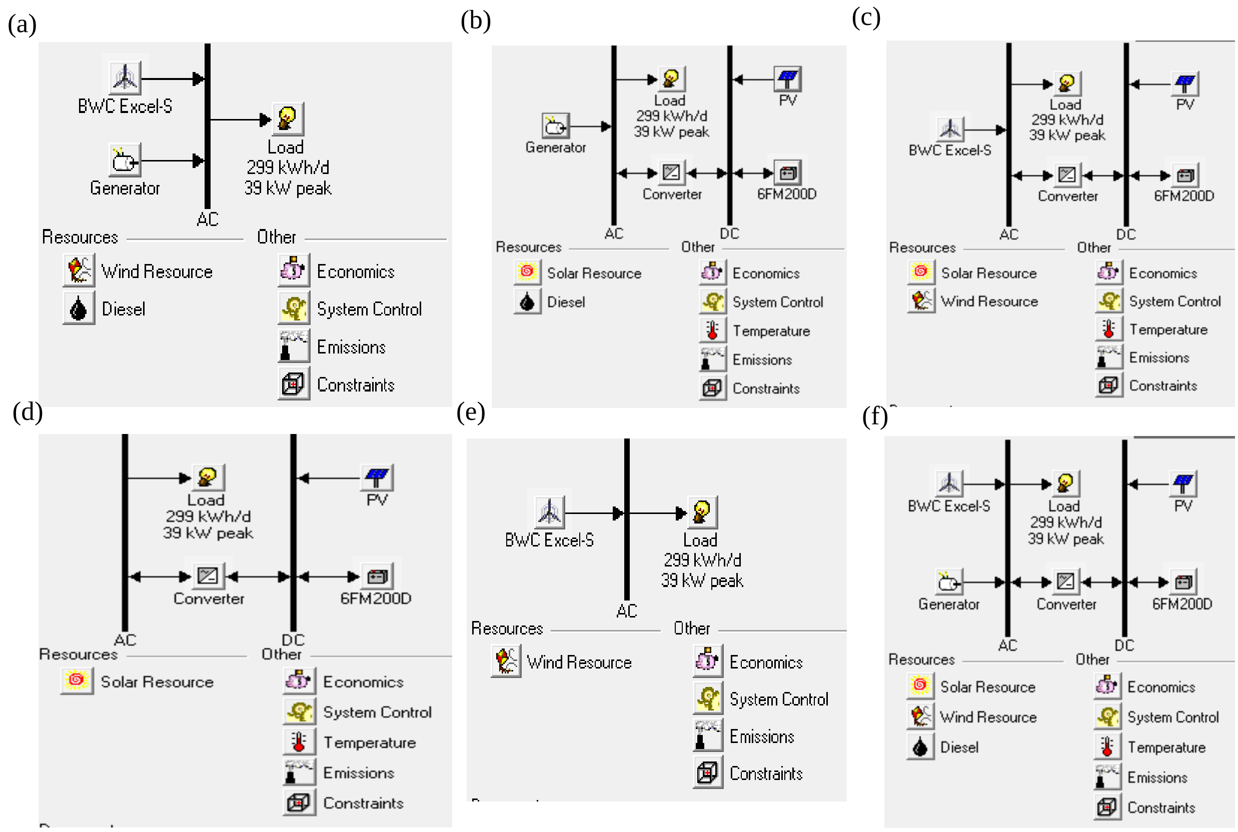

Fig. 9. Design optimization of HRES (a) case-1 (Wind-Generator) (b) Case-2 (PV-Generator) (c) Case-3 (Wind-PV) (d) Case-4 (PV) (e) Case-5 (Wind) (f) Case-6 (Wind-PV-Generator)

9.2 Comparison Analysis

Different load of HRESs in different tropical countries is presented in Table 7. The comparison analysis is performed in order to check our data validity. In [31], an investigation is conducted in Saint Martin island, Bangladesh for a daily load of 78 kWh. The performance of the design is evaluated by using HOMER and result shows that estimated COE is USD0.34/kWh and NPC is USD 136,158. The optimization technique using HOME also is applied in Sitakunda [32] and rural and remote areas [25]of Bangladesh in which COE is calculated as USD 0.36/kWh and USD 0.27/kWh respectively.

Table 5. Comparison of six cases

System	PV (kW)	Battery (No.)	Wind (No.)	Generator (kW)	Converter (kW)	Capital Cost(USD)	Operating Cost(USD/yr)	NPC (USD)	COE (USD)
Case 1 (Wind-Generator)	-	-	42	20	-	1,698,000	37,237	2,222,811	1.45
Case 2 (PV-Generator)	90	225	-	20	25	102,950	25,460	461,781	0.36
Case 3 (Wind-PV)	40	90	12	-	10	515,380	15,199	729,593	0.5
Case 4 (PV)	250	75	-	-	-	113,950	34,058	593,963	0.82
Case 5 (Wind)	-	21	16	-	10	648,960	10,287	793,940	0.58
Case 6 (Wind-PV-Generator)	40	135	3	0.5	22	170,146	13,451	359,729	0.27

Table 6. Electricity generation for six cases

Case	Electricity Production (MWh/year)	Production by components (%)	Excess Electricity (%)
Case 1	995.70	Wind Turbine- 98, Diesel Generator-2	89.1
Case 2	134.45	PV- 89, Diesel Generator-11	16.5
Case 3	331.65	PV-16, Wind-84	66.4
Case 4	333.38	PV-100	82.7
Case 5	371.09	Wind-100	71.8
Case 6	124.77	PV-43, Wind Turbine 56, Diesel Generator - 1	14.8

In [33], an analysis is conducted at Palari areas in India, using various hybrid systems, in which the COE is estimated as USD 0.42/kWh and the NPC as USD 136,158. Simulation by HOMER is also performed in Malaysia [34], Thailand [35] and Turkey [36] where COE is calculated as USD 0.28/kWh, USD 0.59/kWh and USD 0.82/kWh respectively. The comparative study demonstrates that the results obtained from this research are well-matched with other systems and support data authentication.

9.3 Sensitivity analysis

Sensitivity analysis is performed based on considering the uncertain parameters and removing the unrealistic combinations. HOMER shows how the cost of the system changes with a fluctuation in wind energy, solar radiation or prices of the diesel. Different sensitive variables are considered to choose the most appropriate HRES to serve the load demand. In Figure 10, the sensitivity analysis is shown where x and y-axis represent wind speed and diesel cost simultaneously. Similarly, Figure 11 illustrates the difference in solar radiation with different values of diesel price. This type of graphical representation delivers data at specific wind speed and fuel cost where the performance of the system is optimum. Likewise, for a specific solar radiation and fuel cost, an optimal design can be achieved for a particular location because the solar radiation and diesel price are typically site-dependent. Levelized COE values are chosen to represent the figures. The values are spread out over the figure and are expressed in USD/kWh at particular wind speed/solar radiation and diesel price.

Table 7. Different strategies and progress of hybrid systems

Location	Ref.	Load	HRES configuration	Results/Outcomes
Saint Martin Island, Bangladesh	[31]	78 kWh/day	PV size: 8 kW Wind turbine size: 3 kW No. of Battery: 25 (12 V, 200 A h)	COEUSD:0.34/kWh NPC: USD136,158
Sitakunda, Bangladesh	[32]	169 kWh/day	PV size: 27 kW Wind turbine size: 39 kW No. of Battery: 370 (6 V, 225 A h)	COE: USD 0.363/kWh NPC: USD319,132
Rural & Remote areas, Bangladesh	[25]	850 kWh/day	PV size:50 kW Wind turbine size: 40 kW No. of battery:135 (6 V, 225 A h)	COE: USD 0.27/kWh NPC: USD 1,285,761
Palari Areas, India	[33]	492.6 kWh/ day	PV size: 20 kW Hydro size: 30 kW Biodiesel size: 10 kW	COE: USD 0.420/kWh NPC: USD673,147
Remote areas, Malaysia	[34]	1156 kWh/day	PV size: 20 kW Generator 1 size: 50 kW Generator 2 size: 50 KW	COE: USD 0.28/kWh NPC: USD 152,909
Remote island, Thailand	[35]	306 kWh/day	PV size: 15 kW Wind turbine size: 10 kW Diesel generator size: 25 kW Battery capacity: 140 kWh	COE: USD 0.59/kWh NPC: USD 542,027
University, Turkey	[36]	36 kWh/day	PV Size: 120 Diesel Generator Size: 50 No. of battery: 120	COE: USD 0.82/kWh NPC: 1,849,654

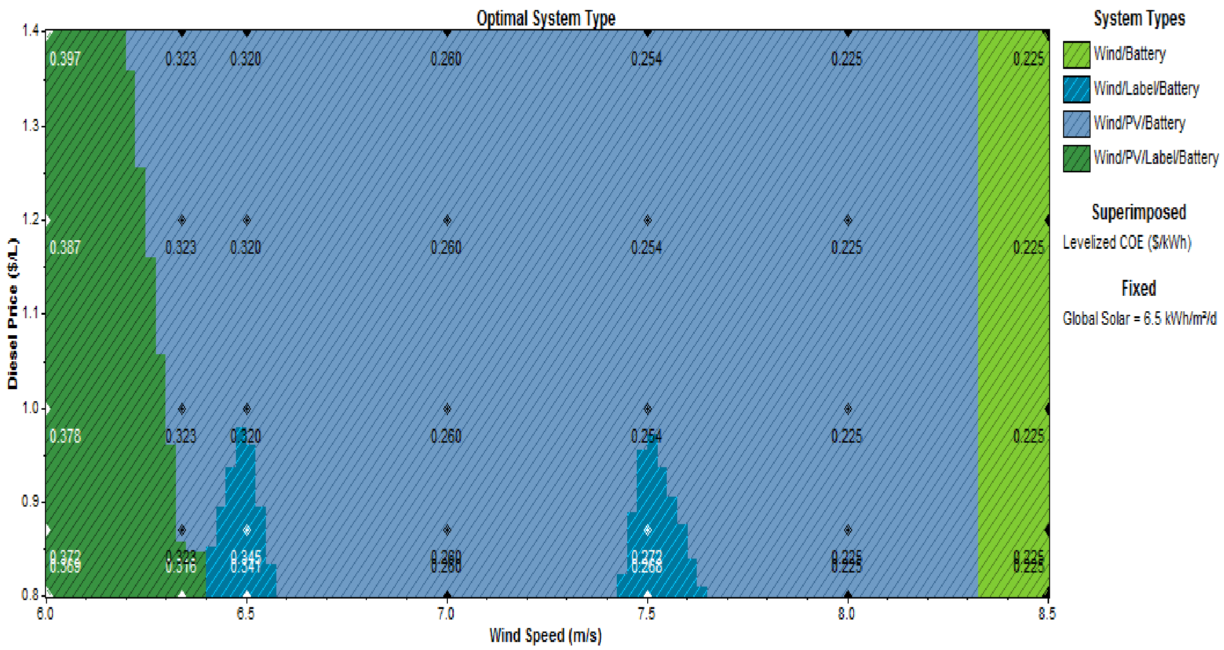

Fig. 10. Sensitivity analysis (variation of diesel price with respect to wind speed)

Figure 10 explains the sensitivity analysis considering the diesel price with the variation of wind speed. The figure shows that the wind velocity which is lower than 6.4 m/s with any chosen diesel price, the PV–wind-generator–battery system is feasible. The system which has wind velocity between 6.4 m/s and 8.4 m/s and diesel price between 1 USD/L or above, the wind–PV–battery system becomes economically feasible. Moreover, when the wind speed is 6.5 m/s and 7.5 m/s and the diesel price is lower then 1 USD/L, wind-generator system delivers optimal design. However, the wind speed above 8.4 m/s and cost of diesel between USD 0.8/L and USD 1.4/L, the wind-battery becomes economically feasible.

Figure 11 reveals the change in diesel cost with respect to solar radiation. The system reflects that wind-generator–battery system is feasible for a fixed solar energy from 4.5 kWh/m²/day to 5.5 kWh/m²/day with any selected diesel cost. However, the system with the solar radiation of 5.5 kWh/m²/day or above and diesel cost of 1 USD/L or above, wind PV-battery system is considered as financially reasonable. The system which has solar radiation smaller than 4.5 kWh/m²/day and diesel cost of USD 0.8/L or more, the wind–PV–battery-diesel system becomes financially attractive. This is in favor of utilizing the PV–wind-diesel–battery system for Saint Martin island.

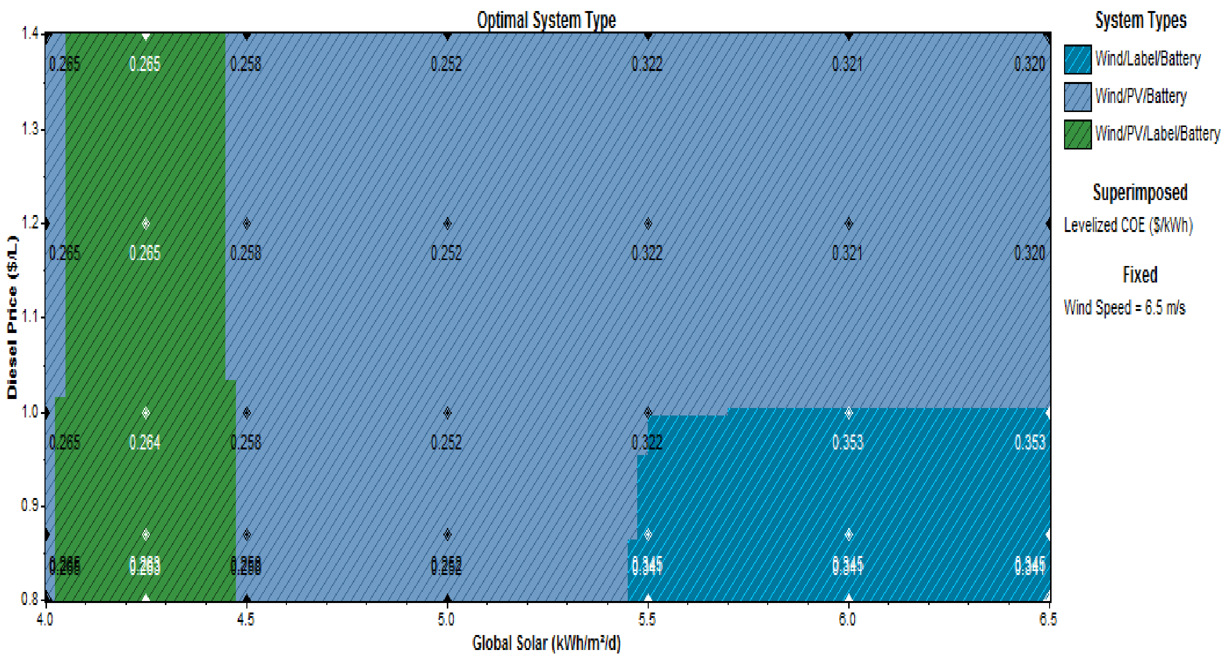

Fig. 11. Sensitivity analysis (variation of diesel price with respect to solar radiation)

Conclusion

HRESs are more feasible than the conventional system since the fuel price has been increasing over the past few years. In addition, HRESs become a promising alternative in comparison to grid connected system, especially in remote islands. It is observed that the Saint Martin island possesses a huge potential for both wind energy and solar energy as it is surrounded by sea. The optimization results successfully prove that hybrid wind/PV/diesel power system delivers the best performance and demonstrates the most cost effective design considering NPC and COE compared to wind/battery power systems and PV/battery system. The study also performs the sensitivity analysis which shows how sensitive the output with a variation of different inputs. The results obtained from the sensitivity analysis will be helpful for the engineers as well as for the designers in term of understanding the effect of uncertainty and making decisions for planning and designing the optimal systems. Nevertheless, to improve the stability of power generation using renewable sources, it is necessary to review and amends the current policies. Further analysis can be carried out by collecting the additional data and performing point by point investigation to improve the effectiveness of the HRERs.

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