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Procedia Engineering 49 (2012) 179 – 188

Procedia Engineering

www.elsevier.com/locate/procedia

Evolving Energy-IEF International Energy Congress (IEF-IEC2012)

Hybrid energy system for St. Martin Island, Bangladesh: An optimized model

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Elsevier use only: Revised 2nd July 2012; accepted date 4th July 2012

Abstract

St. Martin's island is a small island in the Bay of Bengal about 9 km south of the main land of Bangladesh. Nearly 6000 inhabitants live there and fishing is their primary livelihood. Since the island is far away from the main land grid connection is almost impossible in terms of cost and geographic location. However, the electricity demand is partly fulfilled by stand alone diesel generators. In this study, an attempt has been made to model a hybrid electricity generation system for a small community of the island. This system incorporates a combination of solar PV, wind turbine, battery and diesel generator. HOMER software is used to analyze and find out the optimum configuration among a set of systems for electricity requirement for 100 households and 10 shops. The system must satisfy the requirements of 78 kWh/day primary load with 20 kW peak load. Sensitivity analysis is also done to see the impact of solar insolation, PV investment cost, wind speed and diesel fuel price on the optimum result. Solar PV (8 kWp), 2 wind turbines (3 kW) each, diesel generator (15 kW) and 25 batteries (800Ah each) hybrid system is found to be the best among all the configuration in terms of cost of electricity (COE).This configuration gives lowest COE Tk 26.54 / kWh (US$ 0.345/kWh) and total net present cost (NPC) of Tk 10,620,388 (USD$ 137,927) with a renewable fraction of 31%. This system can reduce CO_2 emission by about14 tons per year compared to diesel generator only.

Keywords: Hybrid energy system; Solar PV; Wind; Diesel generator; HOMER.

1. Introduction

St. Martin's island(20° 37′ 57.04″ north latitude and 92° 19′ 11.80″east longitude**)** is a small island in the northeastern part of the Bay of Bengal, about 9 km south of the tip of the Cox's Bazar-Teknaf peninsula, and forming the southernmost part of Bangladesh. The local name of the island is "Narical Gingira" translated from Bangla, meaning 'Coconut Island'. It is the only coral island in Bangladesh.

Most of the island's 6000 inhabitants live primarily from fishing. Besides, the other staple crops are rice and coconut [1]. Being very common in the island, Algae is collected, then dried and finally exported to Myanmar. St. Martin's Island has become a popular tourist spot due to its natural beauty. A survey was done by Local Government Engineering Department (LGED) in 2004 and recorded that the population of the island is about 6000.To meet their electricity demand there are

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 doi:10.1016/j.proeng.2012.10.126

some stand alone diesel generators only but they are not working well. People meet their energy demand through kerosene, coconut palm or by other biomass plants. The island has a good potential of solar and wind resources. Keeping these things in mind HOMER (Hybrid Optimization Model for Electric Renewables), a software has been used to find out the best energy efficient renewable based hybrid system options for the island.

Input information to be provided to HOMER includes: electrical load (primary energy demand), renewable resources (solar radiation, wind speed data), component technical details, cost, constraints, controls etc. The software designs an optimal configuration to serve the desired electric loads. To design the optimum system HOMER performs thousands of hourly simulations. HOMER also performs sensitivity analysis to see the impact of solar insolation, PV investment cost, wind speed and diesel fuel price on the COE [2]. Homer can't model transient changes which are smaller than 1 hour. Economic analysis is very important before installing the system to generate power. HOMER makes this economic analysis and ranks the systems according to their net present cost.

Fig. 1. Aerial view of St. Martin's Island

2. Hybrid Renewable Energy System

In this study solar and wind energy has been used with a diesel generator. The hybrid system consists of an electric load, renewable energy sources (solar and wind) and other system components such as PV, wind turbines, battery, converter [3]. Fig. 1 shows the complete hybrid energy renewable system.

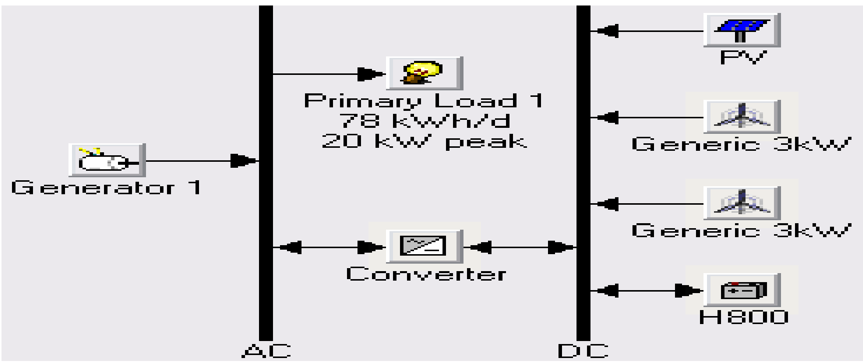

Fig. 2. Complete hybrid energy renewable system

2.1. Electric Load

In this study, a community of 100 households and 10 shops has been considered. This load is based on 3 energy efficient lamps (compact fluorescent bulb, 15 W each), 1 fan (ceiling fan, 40 W), and 1 television (TV, 40 W) for each family and 2 energy efficient lamps (15 W each), 1 fan (40 W) and overall 2 refrigerators (150 W each). Figure 3 shows two load profiles on a day of winter (January) and summer (July).Measured hourly load profiles are not available, so load data were synthesized by specifying typical daily load profiles and then adding some randomness of daily 10% and hourly 15% noise. These have scaled up the annual peak load to 20 kW and primary load to78 kWh/day.

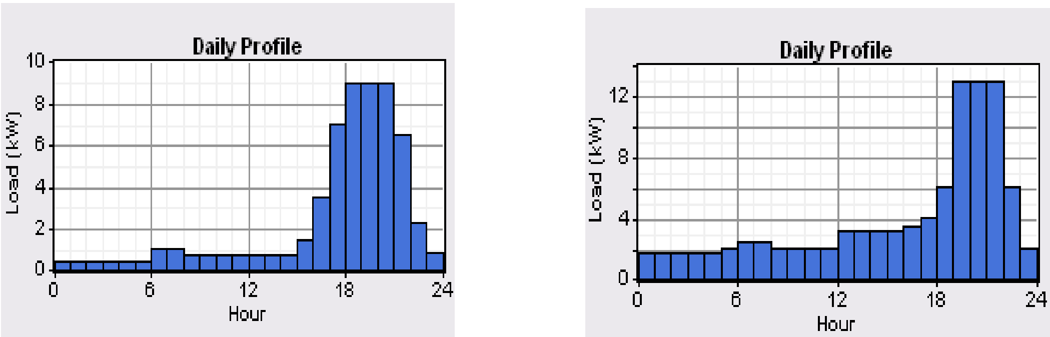

Fig. 3. (a) Load profiles on a day of winter (January); (b) Load profiles on a day of summer (July).

3. Renewable Energy Sources

3.1. Solar Energy

As hourly data is not available therefore monthly averaged global radiation data has been taken from NASA (National Aeronautics and Space Administration) [4]. HOMER introduces clearness index from the latitude and longitude information of the selected site. HOMER creates the synthesized 8760 hourly values for a year using the Graham algorithm. Figure 4 illustrates that the solar radiation is high between February to April. The average annual clearness index is 0.484 and the average daily radiation is 4.549 kWh/m^{2}/d.

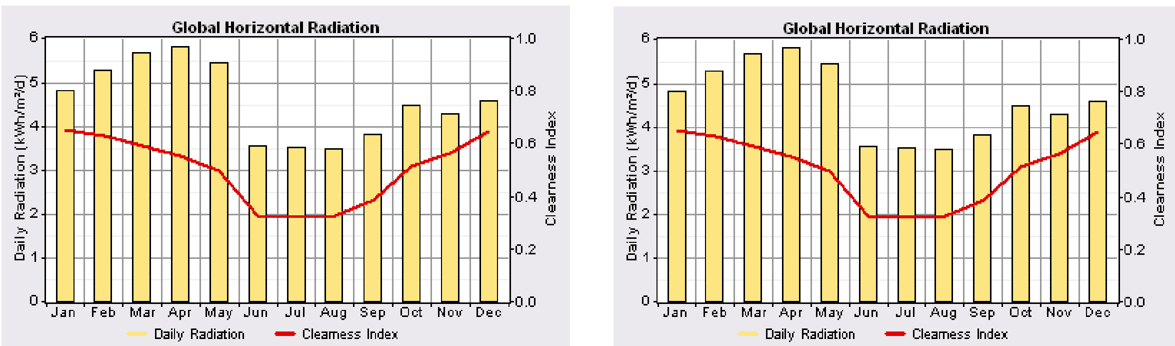

Fig. 4. Solar radiation data throughout the year

3.2. Wind Energy

When hourly data is not available, hourly data can be generated synthetically from the monthly averages. HOMER's synthetic wind speed data generator is a little more different to use than the solar data because it requires four parameters [5].

The Weibull value: k value is a measure of distribution of wind speed over the year. In this study the value of k is taken as 2.

The autocorrelation factor: This factor measures the randomness of the wind. Higher values indicate that the wind speed in 1 h tends to depend strongly on the wind speed in the previous hour. Lower values mean that the wind speed tends to fluctuate in a more random fashion from hour to hour. The autocorrelation factor value is taken as 0.78.

The diurnal pattern strength: It is the measure of how strongly the wind speed depends on the time of the day. In this study, 0.30 is used.

The hour of peak wind speed: It is simply the time of day tends to be windiest on a average throughout the year. In this study, 14 is used as the hour of peak wind speed [6].

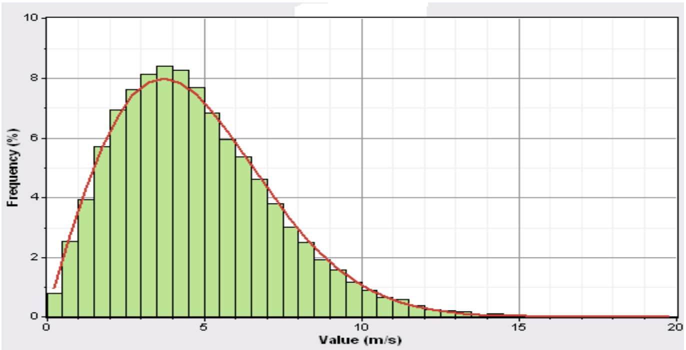

Fig. 5. Probality distribution function of wind speed data synthesized by HOMER

4. Hybrid System Components

The major components of hybrid energy system are PV panels, wind turbines, diesel generator, batteries and converters.For economic analysis , the number of units to be used, capital costs, replacement and O&M costs and operating hours to be defined in HOMER in order to simulate the system.

4.1 Solar Photovoltaic

The cost of PV module including installation has been considered as 250 BDT/W for Bangladesh.Life time of the modules has been taken as 25 years.8 kW and 10 kW PV modules are considered.The parameters considered for the simulation solar PV are furnished in table 1.

Table 1.Solar PV array–technical parameters and cost assumptions

Parameter	Unit	Value
Capital cost	Tk/W	250
Replacement cost	Tk/W	200
Operation and maintenance cost	Tk/W/yr	50
Lifetime	Years	25
Derating factor	Percent	90
Tracking system	No tracking system	0.05

4.2 Diesel Generators

The fuel used in HOMER is modeled by a linear curve characterized by a slope and and intercept at no load. For a capacity range of 15 kW to 45 kW, the slope and the intercept are 0.33 l/h/kW and 0.05 l/h/kW respectively [7]. A diesel generator of 15 kW rated power with technical and economic parameters furnished in table 2.

Table 2.Technical parameters and cost assumptions for diesel generators

Parameter	Unit	Value
Capital cost	Taka(Tk/kW)	10,000
Replacement cost	Tk/kW	8000
Operation and maintenance cost	Tk/h	30(15 kW)
Operational lifetime	Hours	15,000
Minimum load ratio	Percent	10
Fuel curve intercept	$l/h/kW_{rated}$	0.05
Fuel curve slope	$l/h/kW_{output}$	0.33
Fuel price	Tk	56

4.3 Wind Turbine

For the hybrid system a Generic 3 kW wind turbine has been considered [8]. Technical and economic parameters for selected wind turbine are furnished in table 3.

Table 3.Technical and economic parameters of wind turbine

Parameter	Unit	Value
Rated power	kW	3
Starting wind speed	m/s	4
Rated wind speed	m/s	13
Cut-off wind speed	m/s	15
Capital cost	Tk/kW	200,000
Replacement cost	Tk/kW	150,000
Operation and maintenance cost	Tk/year/turbine	10,000
Lifetime	Years	20

4.4 Battery

The Hoppecke 8 OPzS storage batteries are utilized in the hybrid system [9].The specifications are shown in table 4.

Table 4.Technical parameters and cost assumptions for battery

Parameter	Unit	Value
Nominal voltage	Volt	2
Nominal capacity	Ah(kWh)	800(1.6)
Maximum charge current	A	162
Round-trip efficiency	Percent	86
Minimum state of charge	Percent	30
Capital cost	Tk/kWh	7000
Replacement cost	Tk/kWh	6000
Operation and maintenance cost	Tk/kWh/yr	50

4.5 Converter

A converter is required to convert AC-DC or DC-AC. Table 5 shows the technical and economic parameters for converter.

Table 5.Technical parameters and cost assumptions for converter

Parameter	Unit	Value
Capital cost	Tk/kW_{rated}	14,933
Replacement cost	Tk/kW_{rated}	10,000
Lifetime	Years	10
Efficiency	Percent	90
Rectifier capacity	Percent	95
Rectifier efficiency	Percent	85

4.6 Hybrid System Control Parameters and Constraints

The project life has been considered to be 25 years and the annual real interest gas been taken as 5%.The capacity shortage penalty is not considered. The spinning reserve and system constraints are furnished in table 6 and 7 respectively.

Table 6.Spinning reserve inputs

Percent of annual peak load	0
Percent of hourly load	8
Percent of hourly solar output	0
Percent of hourly wind output	35

Table 7.Constraints used in HOMER

Parameter	Value
Maximum unserved energy	0(%)
Maximum renewable fraction	0 to 100%
Maximum battery life	N/A
Maximum annual capacity shortage	0 and 5%

5. Results and Discussion

To evaluate the performances of different hybrid systems in this study, optimal systems' performance and the sensitivity analysis have been carried out using HOMER simulation tools. In this software the optimized results are presented categorically for a particular set of sensitivity parameters like solar radiation, wind speed, diesel price, maximum annual capacity shortage and renewable fraction. HOMER performs thousands of hourly simulations over and over in order to design the optimum hybrid system.

6. Optimization Results

Simulations have been conducted considering different values for solar radiation, wind speed, minimum renewable fraction, and diesel price providing more flexibility in the experiment. The optimization results for specific wind speed 4.71m/s, solar irradiation 4.5486kWh/m^2/d and diesel price 56 taka are illustrated in figure 5. It is seen that a PV, wind turbine, diesel generator and battery hybrid system is economically more feasible with a minimum COE of tk.26.54/kWh and a minimum NPC of 10,620,388.

The hybrid system comprised of 8 kW PV array, two wind turbines (3 kW each), a diesel generator with a rated power of 15 kW and 25 storage batteries in addition to 10 kW is found to be the most feasible system. Figure 6 shows the details related to energy generated by PV, wind turbine and diesel generator system, excess electricity, un-met load, capacity shortage and renewable fraction for the most economically feasible system applicable for the selected location.

Sensitivity variables

Global Solar (kWh/m²/d) 4.55 Wind Speed (m/s) 4.71 Diesel Price ($/L) 56

Max. Annual Capacity Shortage (%) 0

Double click on a system below for simulation results. Categorized Overall Export...

PV (kW)	G3	G3	Gen1 (kW)	H800	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
8	1	1	15	25	10	CC	$ 2,979,330	542,152	$ 10,620,388	26.539	0.31	0.00	7,787
8	1	1	15	30	10	CC	$ 3,035,330	539,031	$ 10,632,407	26.575	0.31	0.00	7,735
8	1	1	15	25	15	CC	$ 3,053,995	547,821	$ 10,774,954	26.928	0.29	0.00	7,868
8		1	15	30	10	CC	$ 2,835,330	565,547	$ 10,806,119	27.006	0.26	0.00	8,252
8		1	15	25	10	CC	$ 2,779,330	570,407	$ 10,818,620	27.032	0.25	0.00	8,329
10	1	1	15	25	10	CC	$ 3,479,330	521,889	$ 10,834,804	27.077	0.34	0.00	7,466
8	1		15	30	10	CC	$ 2,835,330	567,965	$ 10,840,195	27.091	0.26	0.00	8,252
10	1	1	15	30	10	CC	$ 3,535,330	518,410	$ 10,841,770	27.098	0.34	0.00	7,378
8	1	1	15	25	18	CC	$ 3,098,794	550,019	$ 10,850,735	27.117	0.29	0.00	7,872
8	1		15	25	10	CC	$ 2,779,330	572,825	$ 10,852,695	27.117	0.25	0.00	8,329
8	1	1	15	20	10	CC	$ 2,923,330	562,629	$ 10,852,989	27.119	0.29	0.00	8,059
8	1	1	15	20	15	CC	$ 2,997,995	559,787	$ 10,887,596	27.206	0.29	0.00	8,013
8	1	1	15	20	18	CC	$ 3,042,794	561,641	$ 10,958,537	27.383	0.29	0.00	8,013
8	1	1	15	30	15	CC	$ 3,109,995	557,343	$ 10,965,158	27.397	0.28	0.00	7,988
10		1	15	30	10	CC	$ 3,335,330	542,766	$ 10,985,048	27.447	0.29	0.00	7,869
8		1	15	25	15	CC	$ 2,853,995	577,079	$ 10,987,316	27.457	0.24	0.00	8,398
8		1	15	20	10	CC	$ 2,723,330	586,396	$ 10,987,968	27.457	0.25	0.00	8,522
10		1	15	25	10	CC	$ 3,279,330	547,016	$ 10,988,939	27.466	0.29	0.00	7,940
10	1	1	15	25	15	CC	$ 3,553,995	527,567	$ 10,989,491	27.460	0.32	0.00	7,542

Note: All the currency values were considered in terms of Tk (Taka, Bangladeshi currency) instead of $ (USD).

Fig. 6: Optimization results for PV-diesel-wind turbine-battery system for a solar radiation of 4.549 kWh/m$^{2/}$d, diesel price of 56 Tk./L, maximum capacity shortage of 0%.

System Architecture: 8 kW PV; 1 Generic 3kW; 1 Generic 3kW; 15 kW Generator 1; 25 Hoppecke 8 OPzS 800; 10 kW Inverter; 9.5 kW Rectifier; Cycle Charging

Total NPC: $ 10,620,388
Levelized COE: $ 26.539/kWh
Operating Cost: $ 542,152/yr

Cost Summary | Cash Flow | Electrical | PV | G3 | G3 | Gen1 | Battery | Converter | Emissions | Time Series

Production	kWh/yr	%
PV array	12,882	34
Wind turbines	5,312	14
Generator 1	19,704	52
Total	37,899	100

Consumption	kWh/yr	%
AC primary load	28,394	100
Total	28,394	100

Quantity	kWh/yr	%
Excess electricity	5,024	13.3
Unmet electric load	3.19	0.0
Capacity shortage	9.74	0.0

Quantity	Value
Renewable fraction	0.306
Max. renew. penetration	2,871 %

Fig. 7: Energy generated by PV, wind turbine and diesel generator system, excess electricity, un-met load, capacity shortage and renewable fraction

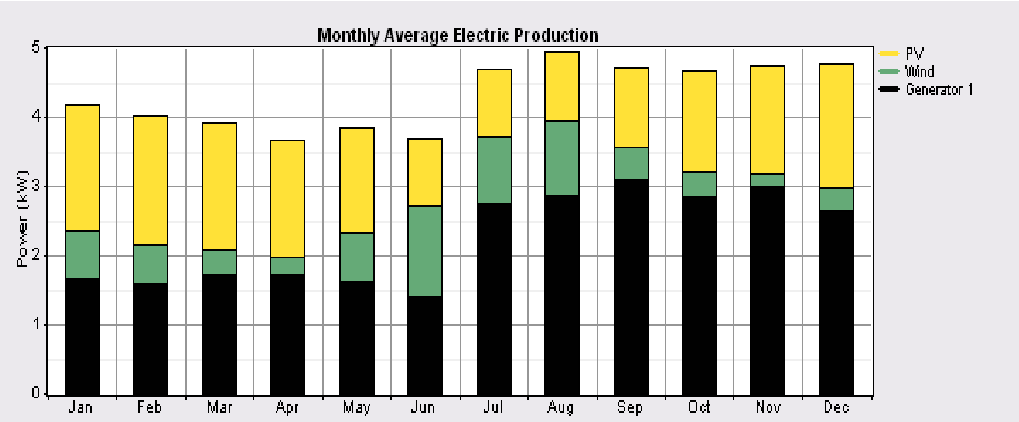

Fig. 8: Energy yield for the feasible hybrid PV-diesel-wind-battery system

7. Sensitivity Results

Sensitivity analysis is a measure that checks the sensitivity of a model when changing the value of the parameters of the model and also changing the structure of the model. In this paper sensitivity analysis has been undertaken to study the effects of variation in solar radiation, wind speed and diesel price to make appropriate recommendations in developing a hybrid renewable energy system. Figure 7 shows optimization results in terms of wind speed and diesel cost. Figure 8 exhibits the sensitivity analysis results in terms of global solar radiation and diesel price for maximum annual capacity shortage of 0%.

The system shown in figure 7 and 8 reflects that PV-diesel-battery system feasible for any selected diesel price with a fixed wind speed of 3.5m/s. For 3.5m/s wind speed or more and diesel price of 80 taka/L or more, wind-PV-diesel-battery hybrid system becomes economically more feasible.

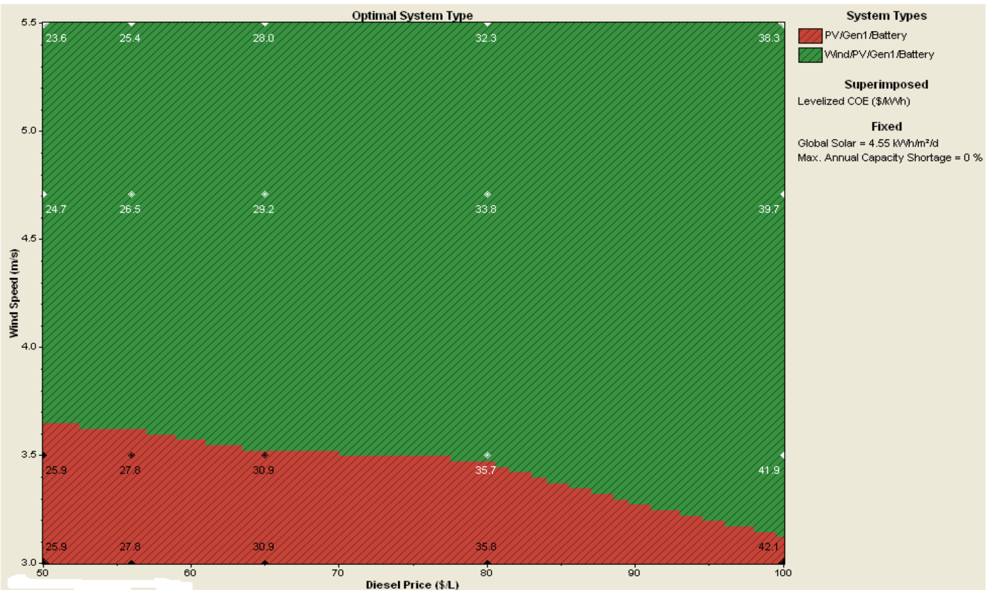

Fig. 9: Type of optimal system in terms of wind speed and diesel price with global solar radiation 4.55 kWh/m^2/d, maximum annual capacity shortage 0%.

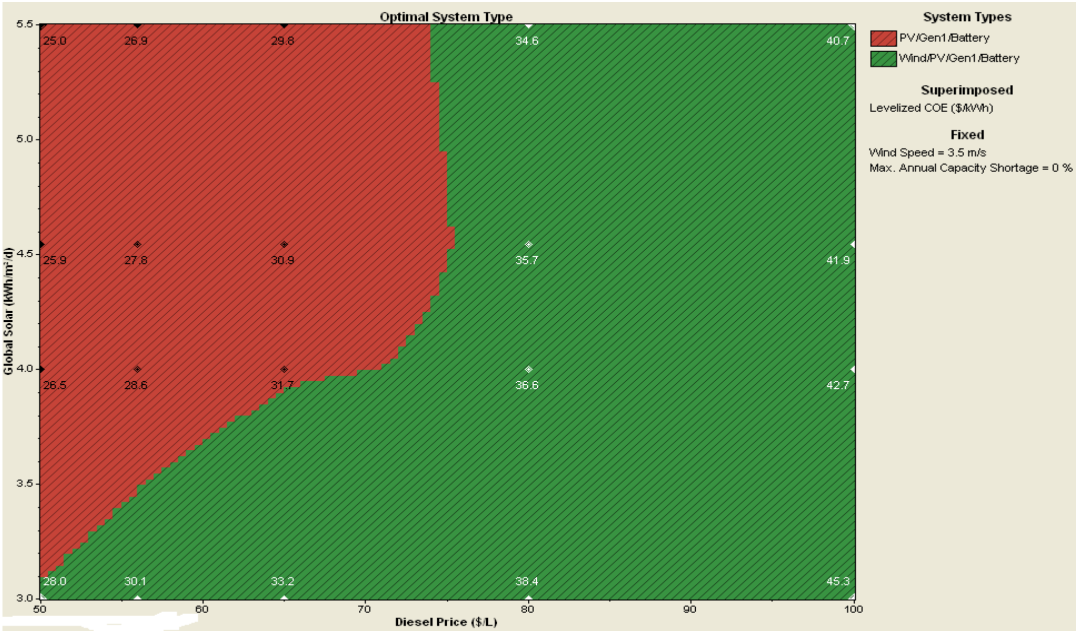

Fig. 10: Type of optimal system in terms of solar radiation and diesel price with wind speed 3.5 m/s, maximum capacity shortage of 0%.

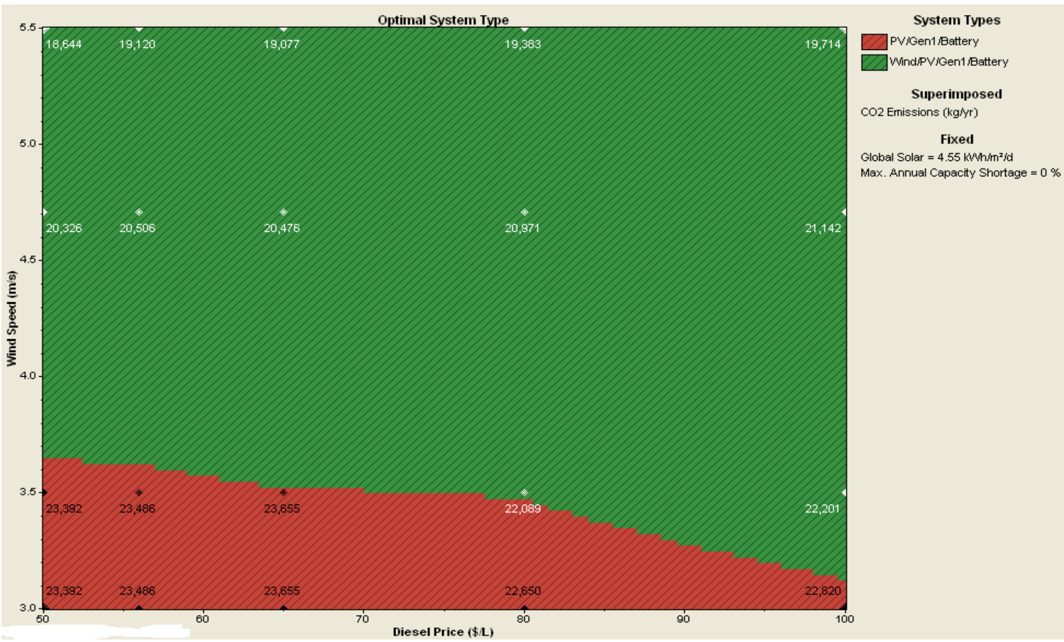

Fig. 11: Annual emissions (kg/year) of CO_2

8. Emission Analysis

Power generation with renewable energy sources reduces the emission of CO_2, SO_2, NO_X to the atmosphere. A PV-wind-diesel hybrid energy system emits 20,506 kg/yr of CO_2 and 50.6 kg/yr of CO while only diesel generator emits 34,206 kg/yr of CO_2. Fig. 11 show the emissions of carbon dioxide for two different systems such as PV-diesel-battery and wind-PV-diesel-battery.

9. Conclusions

The study simulates a PV-wind –diesel-battery hybrid energy system in St. Martin Island. A system with 8 kW PV array along with a 15 kW diesel generator and 25 numbers of batteries (nominal capacity 800 Ah, nominal voltage 2V each) gives the most economically feasible solution. In Bangladesh the price of diesel fuel is increasing very rapidly. So using only diesel generators will not be feasible in near future. Experimental result shows that the COE of the optimized system is tk. 26.54/kWh with 31% renewable fraction. Net present cost (NPC) and operating cost for the optimized system are tk. 10,620,388 and tk./yr 542,152 respectively. This hybrid energy system reduces the emission of CO_2 significantly which reduces global warming which is a matter of headache all over the world.

Acknowledgements

The authors would like to thank the Mechanical and Chemical Engineering Department of IUT. All mistakes remain ours.

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