DOI: http://doi.org/10.5281/ zenodo.3996286 Journal of Energy & Technology (JET)
Vol. 1, No. 1, 2020

Techno-Economic Evaluation of Hybrid Supply System for Sustainable Powering the Saint Martin Island in Bangladesh

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***Abstract*— With the progression of new technology, renewable energy (RE) based supply systems are becoming popular day by day. The main concern of this work is to examine the viability of renewable energy-oriented hybrid systems for powering the Saint Martin Island, the southern area of Bangladesh. This work proposed a hybrid solar PV/wind turbine (WT) arrangement to provide a way out to the power crisis of off-grid Saint Martin Island with optimizing hybrid power generation schemes focused on the locally obtainable renewable resources. The techno-economic feasibility of the hybrid solar PV/WT system along with back supply such as diesel generator (DG) and battery bank (BB) has been critically analyzed using the HOMER optimization software with genuine climate statistics and nominal load profile under the condition of summer and winter seasons. Simulation results find that the RE focused supply system technically feasible and includes a minimum amount of total net present cost (TNPC) along with the lower value of per unit electricity generation cost. Moreover, the amount of released gas for the RE focused supply system is far less than the gas released if the total electrical load was supplied by only diesel generators. Finally, the hybrid solar PV/WT system along with backup supply is a realistic solution which includes the initial cost of 89,620 $, the replacement cost of $ 59,791, operating cost of 22,701 $/year, TNPC of 250,919 $ and electricity generation cost of 0.206 $/kWh.**

Keywords*— Renewable energy, Hybrid energy, Saint Martin

I. INTRODUCTION

Due to the colossal increment of power utilization over the last few decades, carbon contamination and environmental change caused by fossil fuel utilization in power generation has been considered as a critical environmental crisis and got extensive attention [1]–[6]. In current eras, energy has come to be an elementary requirement for the human lifespan. Devoid of energy, up-to-date advancement cannot be determined. Fossil energy has played a dynamic role to achieve the energy prerequisite of earth. As a consequence of recent stores and deployment rates of fossil assets, the world will bring about 122 years for coal, 42 years for oil, and 60 years for natural gas [7]. Comprehensively, there will be a 36% upsurge in fossil fuel energy ingestion between the years 2011 and 2030 if the annual consumption level is 1.6% [8]. On the other hand, the dreadful conditions of fossil fuels stand-in have been witnessed globally over the most recent decades. In addition, the consumption rate of fossil fuels has been going up meaningfully equated to the inadequate reservation. Globally, there is a 13.5% upsurge in fossil-based power generation even though the non-fossil sources have deteriorated by 10.8% between the only two decades [9]. For that reason, the world is in front of some severe concerns for instance global warming and CO_2 emissions [10]–[15]. Because of the environmental pollution and resource degradation of fossil fuels, the introduction of alternative energy sources has achieved great consideration to come across the current energy demand. However, with the advancement of new technology [16]–[21] the world is moving toward renewable energy and the researchers are always trying to find out an efficient way to utilize renewable energy sources.

Energy has an important part in the financial as well as social progress of Bangladesh. On the other hand, the ease of access of electricity cannot be provided in an unbroken, reasonable, and dependable way. The country has attained only 62% access to electricity (together with renewable energy) and the generation of electricity per capita is only 332 KWh [22], [23]. There are a lot of localities in Bangladesh, particularly in off-grid regions similar to Saint Martin Island, which have no right of entry to a consistent power source. Providing energy to remote areas in a justifiable approach is an elementary necessity at present because of the reduction of fossil fuel assets, fuel cost acceleration related to conventional energy generation, population growth, and insufficient waste clearance conveniences. Besides, as a result of the international consciousness of global warming and the scarcity of supply of natural gas and oil, renewable energy-based power plants have become encouraging replacements and have been rising promptly. The Bangladesh government is financing significantly in renewable energy and has acquainted with renewable energy policy anticipating to implement renewable energy-based power plants to achieve 10% of the total power demand by 2020 [24]. Photovoltaic solar and wind generation units are the smartest selections for supplying electricity to rural and remote areas where utility lines are luxurious to acquaint with because of the landscape [25]–[30].

Renewable energy resources (RES) have grown a lot of attention and turn out to be suitable replacements for fossil fuel resources. Renewable energy sources have enough potential to fulfill the present and future energy demand of residential load, and cellular network [31]–[36]. Despite the potential benefits, there are some challenges of harvesting renewable energy because of the dynamic nature of RES and high installation cost as compared to the convention non-renewable energy sources [37]–[40]. The combined utilization of RES with the non-renewable RES can overcome this problem and enhance the reliability of the supply system. Moreover, a new strategy namely hybridization of renewable energy sources (HRES) is implemented to address these challenges [41]–[45]. Hybrid utilization of renewable energy sources can be functioned both in with grid and without grid mode that comprises numerous renewable energy and energy storage systems. HRES has to turn out to be a widely held choice especially for providing electricity in rural and isolated areas. Because of the intermitted source along with the lack of ability of renewable sources, the energy storage structure can be added as backup sources to provide a consistent and uninterrupted source of electricity. In contrast, when additional generation is possible by renewable sources, the supplementary power can be either put in storage in the energy storage or can hand on to the utility grid. HRES delivers a lot of benefits for example it decreases COE, drops CO_2 emission, as well as supplies reasonably priced electricity in isolated, countryside areas as well as Islands [46]–[49]. Overall the qualities encounter the requirement of sustainable development (SD) in terms of social, economic, and the environment.

In this manuscript, a hybrid scheme together with wind energy, solar PV, and the diesel generator has been recommended to propose the optimum size of HRES's equipment at Saint Martin Island in Bangladesh. Ever since the sunbeams are not available throughout the night and wind speed is fluctuating for the day, a diesel generator can be acquainted with to escape intermittent supply of power. To achieve the objectives, a well-known software instrument, named HOMER, is used to determine the finest scheme of HRES for the Saint Martin Island, Bangladesh.

II. LITERATURE REVIEW

In current periods, energy has come to be an elementary requisite for human life. With the advancement of new technology such as wireless communication [50]–[56], internet of thing [57], [58], navigation, satellite communication, etc. the world is suffering from power crisis. As a consequence, researchers are always trying to find out alternative energy sources. There has been substantial research done on a different combination of hybrid systems. In [5], [47], [48], [59] a hybrid generation model, mostly based on Photovoltaic (PV)-Wind-Diesel Generator (DG)-Battery system are discussed on various perspective. Most of them implemented their proposed model in HOMER. In terms of solar radiation energy, most of them used the Graham algorithm for producing realistic hourly data. Authors in [47] proposed a PV-Wind-Grid associated hybrid energy system model for hilly areas of Bangladesh and found it cost-effective. For decentralized or remote areas, a PV-Wind-DG-Battery hybrid system is proposed in [5] and also found it feasible and optimized. Various combination of renewable energy source with fossil fuel-based generation system is compared in [48] to identify a configuration that run into the looked-for system reliability necessities with the lowest electricity unit cost. To meet the residential load in Dhaka city a PV-DG-Battery based hybrid energy generation system has been proposed in [59]. The authors used HOMER software simulation to demonstrate their proposed model and found that the proposed model can significantly reduce the dependence of fossil fuel. A solar home system (SHS) for off-grid areas of Bangladesh and its limitation over various natural calamities and weather has been discussed in [60]. Due to its low back up time and others, limitations authors suggest some alternative solutions with their proposed SHS model. In [61] micro concentrated solar power (Micro CSP) and its applications on the various field has been discussed with its socio-economic aspect. Authors found micro CSP is feasible and has untapped potential in different sectors in Bangladesh. Biomass energy from different sources and its prospect in various fields are discussed in [41]–[43], [62]. A case study is on biomass gasification to generate power from rice husk and its future contribution in the rural electrification and industrialization prospect is presented with data and graph in [41]. The future probability to generate power from biogas and biomass source in Bangladesh is studied in [42] as there is a large amount of biomass source is available here. For being an expensive system, a poor population cannot afford a biomass plant alone. So community-based biogas project is proposed to back up that problem and also provide a sustainable solution for the energy crisis [43]. A prospect of biogas based power plants for commercial usage has been studied in [62]. Authors are worked out with complete design including system specification. After detailed energy generation and cost analysis, they concluded that the investment may return within eight to nine years. Several types of research have been worked out on hybrid power generation to meet up increasing demand of power the coastal area and Islands of Bangladesh [54]–[56], [63], [64]. A hybrid energy system based on tidal and wind power generation is combined with diesel generator has been proposed for Kutubdia Island, Bangladesh [56]. Considering different load and wind-tidal-diesel combinations they have used HOMER to optimize the best efficient system. A PV and wind turbine based hybrid system has been simulated in HOMER by considering a hybrid model for Sandwip, the Island of Bangladesh [54]. The author has used PV solar module and Vestas V82 wind turbine for simulation. Another study on solar PV, wind, and the biomass-based hybrid system has been taken out for Sandwip [55]. Authors have found the only renewable energy-based system is too expensive and suggests combining both renewable energy sources and fossil fuel. Authors in [64] have considered diesel power generators besides PV, wind, and Biomass-based hybrid systems in case of sudden heavy load for Saint Martin Island in Bangladesh. By analyzing and comparing different method they have concluded their model is more feasible and cost-effective. A hybrid energy system based on PV panels, wind turbines, diesel generator, batteries, and converter has been studied in [63]. They simulate their model in HOMER by considering different components of their proposal and found the most economically feasible solution for generating power to meet up the demand of energy in Saint Martin Island.

III. DATA ACQUISITION

Saint Martin Island is a small island with an area of only 3.37 square kilometers 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. It is about 7 km west of the northwest coast of Myanmar, at the mouth of the Naf River as depicted in Figure 1.

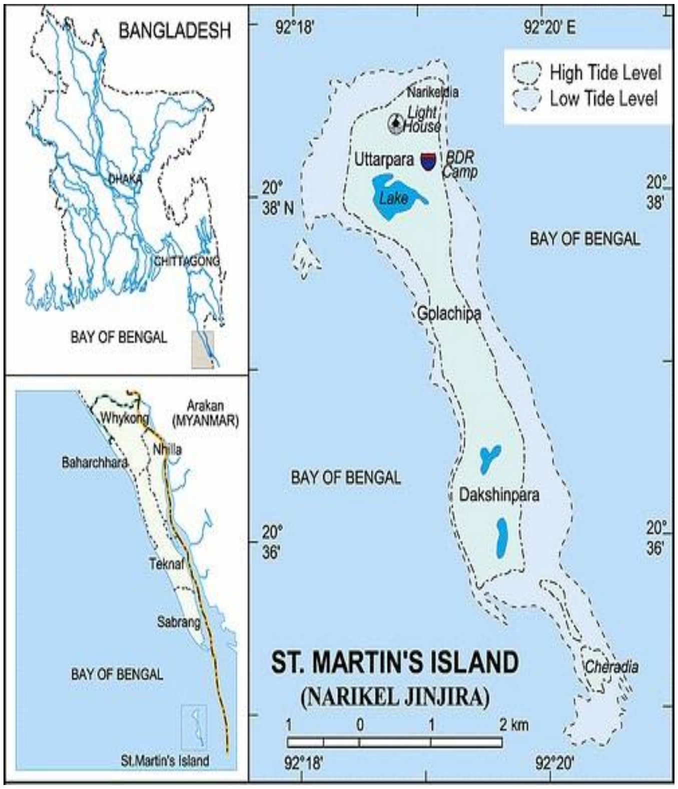


Figure 1: Saint Martin Island.

According to the census conducted by the Statistics and Information Division, Ministry of Planning, Government of the People's Republic of Bangladesh, there is a population of 6,703 with 850 households [65]. The yearly electric energy demand was found at about 1168 MWh [65]. There was a 30 kW diesel generator in Saint Martin Island launched by Bangladesh Power Development Board (BPDB), but it is not in operation anymore. People meet up their basic energy demand by using kerosene, coconut, and palm or by other biomass resources. Some of the commercial shops and hotels meet their electricity demand by a diesel generator. The Island has a school that makes education possible for children in the Island to complete up to their secondary education. There is also a health clinic on the Island [65].

A. Field Survey :

There is no electrical grid connection on the Island because of its location in the middle of the Bay of Bengal. There are some privately owned generators, which run for 4 hours each day from 6 pm to 10 pm. People can take electricity connections from these generator lines, however, one is only allowed to use two lights and one small fan in these 4 hours. For running such a small load, one has to pay BDT 20/day. This high electrical charge is a big burden for the majority of people on the Island. Hence, after sunset, the majority of the Island is covered in darkness. Because of this condition, the security situation of the area is highly hampered. A small fraction of the people has installed Solar Home System (SHS) in their homes.

B. Estimation of Primary Load :

In this subsection, the primary load of the Island is calculated for summer and winter. The summer stays from March to October and the winter stays from November to February. The primary demand of the location is calculated for 850 families, 15 hotels, 100 shops, 1 school, and 1 hospital under the two seasons.

1) Household Load: The individual households were assumed to use 3 units of 25W lights for 6 hours between 5 pm-11 pm, 2 units of 70W fan in operation from 6 pm to 6 am and TV of 15W is to be in operation in each household on average basis starting from 6 pm to 10 pm in Summer. The detail of the load for households is presented in Table I.

Table I: Energy consumed by the households

Appliances	Quantity	Capacity (W)	Summer		Winter	
			Hours of Operation (hours/day)	Watt Hour/day	Hours of Operation (hours/day)	Watt Hour/day
CFL	3	25	6	450	8	600
Fan	2	70	12	1680	0	0
TV	1	20	4	80	4	80
Total (for one house)			2210		680	
Total Load for 850 houses			1878500		578000	

Table II: Energy consumed by the hotels.

			Summer		Winter	
Appliances	Quantity	Capacity (W)	Hours of Operation (hours/day)	Watt Hour/day	Hours of Operation (hours/day)	Watt Hour/day
CFL	3	25	6	450	7	525
Fan	1	70	7	490	0	0
TV (for standard hotels)	1	20	4	80	4	80

2) Hotel Load: Table II implies that a single room (standard hotel) power consumption in summer =1020 watt-hour/day and in winter= 605 watt-hour/day.

For a single room (economy hotel) power consumption in summer = 940 watt-hour/day and in winter=525 watt-hour/day. In Saint Martin Island, 5 standard hotels, 10 economy hotels and 10 rooms in each hotel. Power consumption for 5 standard hotels in summer =51000 watt-hour/day and in winter=30250 watt-hour/day. Power consumption for 10 economy hotels in summer =94000 watt-hour/day and in winter= 52500 watt-hour/day.

Total Load for 15 hotels = 145000 watt-hour/day (summer) and 82750 watthour/day (winter)

2) Commercial Load: There are around 100 shops on the Island, most of which are owned by the residents of the Island. A regular shop uses a fan of 70W and a light of 20W. The fan is assumed to be in operation from 10 am-10 pm, whereas the light load is in use in the evening time, i.e. during 6 pm-10 pm for 4 hours in summer. The detail of the load for households is presented in Table III

Table III: Electric load consumption of a shop.

			Summer		Winter	
Appliances	Quantity	Capacity (W)	Hours of Operation (hours/day)	Watt Hour/day	Hours of Operation (hours/day)	Watt Hour/day
CFL	1	20	4	80	5	100
Fan	1	70	12	840	0	0
Total (for one shop)			920		100	
Total Load for 100 shops			92000		10000	

4) School Load: Quality education for any community is essential for the socio-economic development of one country. To meet this essential requirement, a primary school is present which allows the student to complete up to class 5.

In our project, we assumed that there are 20 lights each of 20W and 5 fans each of 70W in operation for 6 hours each day from 9 am-3 pm for the school load. The detail of the load for schools is presented in Table IV.

Table IV: School electrical load consumption

			Summer		Winter	
Appliances	Quantity	Capacity (W)	Hours of Operation (hours/day)	Watt Hour/day	Hours of Operation (hours/day)	Watt Hour/day
CFL	20	25	6	3000	6	3000
Fan	5	70	6	2100	0	0
Total load			5100		3000	

5) Health Clinic Load: There is a health clinic present on the Island which is a basic service center equipped to treat minor illness for the surrounding communities. The main appliances that draw electric power in this clinic are LED lights, fans, communication radio, laboratory microscope, and vaccine freezer. It is assumed that the health clinic uses 8 LED lights of 3W each, from 9 am-4 pm for 7 hours, the 3 fan loads of 15W, and is in operation from 9 am-4 pm for 7 hours. It is proposed that the clinic is equipped with 1 unit of 20W microscope which works for 4 hours each day from 9 am-1 pm. The communication radio of 5W is assumed to work for 7 hours from 9 am-4 pm and 1 unit of 60 W vaccine freezer is assumed to be in operation for 24 hours. The detail of the load for health clinics is presented in Table V. Moreover, a summary of the total load for the Saint Martin Island is presented in Table VI.

Table V: Health clinic electrical load consumption

			Summer		Winter	
Appliances	Quantity	Capacity (W)	Hours of Operation (hours/day)	Watt Hour/day	Hours of Operation (hours/day)	Watt Hour/day
CFL	5	25	7	875	7	875
Fan	3	70	7	1470	0	0
Vaccine freezer	1	60	24	1440	24	1440
Laboratory microscope	1	20	4	80	4	80
Total load			3865		2395	

TABLE VI: Total load calculation

Different Types of Load	Total Consumption (kWh/day)	
	Summer	Winter
Domestic Load	1878.5	578.0
Hotel Load	145.0	82.75
Commercial Load	92.0	10.0
School Load	5.1	3.0
Health Clinic Load	3.865	2.395
Total	2124.465	676.145

C. Estimation of Load Profile :

The load profile will not be the same throughout the year, as during winter months, the fan load will not be in operation. So there will be two separate load profiles, 1) March-November 2) December-February.

TABLE VII: Primary load input into HOMER

Time	Load in kW for Summer	Load in kW for Winter
00:00 - 01:00	135.020	0.06
01:00 - 02:00	135.00	0.06
02:00 - 03:00	135.00	0.06
03:00 - 04:00	135.00	0.06
04:00 - 05:00	135.00	0.06
05:00 - 06:00	135.00	0.06
06:00 - 07:00	75.45	0.06
07:00 - 08:00	75.45	0.06
08:00 - 09:00	15.950	0.06
09:00 - 10:00	0.924	0.56
10:00 - 11:00	7.924	0.56
11:00 - 12:00	7.924	0.56
12:00 - 13:00	7.944	0.58
13:00 - 14:00	7.220	0.58
14:00 - 15:00	7.220	0.58
15:00 - 16:00	7.220	0.06
16:00 - 17:00	15.950	0.06
17:00 - 18:00	190.145	65.935
18:00 - 19:00	244.770	102.81
19:00 - 20:00	244.770	102.81
20:00 - 21:00	244.770	102.81
21:00 - 22:00	244.770	102.81
22:00 - 23:00	215.770	82.81
23:00 - 00:00	215.770	82.81

In the load profile of Table VII, that major load contributor is the domestic load. All the other loads, such as commercial load, school load, health clinic load account for the very little amount of the total load compared to the load of 850 households. It can also be seen from the load profile that during March-November, the load remains fairly consistent in sections i.e. from 10 pm to 6 am of the next day the load remains between 216 kW to 135 kW. There is a big spike in load demand during the evening time of summer when light load and TV load of the domestic household is added. Between 6 pm-10 pm, the load is almost consistent remaining at 245 kW.

During winter, December to February, the load profile will be different from summer, March to November. This is because, during winter, the fan load will not be in operation. As fan load in 850 households will account for a large amount of load, a separate load profile is constructed. Table VII also shows the daily load profile during the winter months. The load is very small during most parts of the day, as the fan load which is the main load during the day time in summer is not in operation. Between midnight to 5 pm the next day, the load is very small. However when the sun sets, the entire light load is turned on, and there is a spike in the load profile. The load remains consistent between 6 pm to 10 pm at 102.81 kW.

IV. PROPOSAL FOR DIVIDING THE ISLAND INTO FOUR REGIONS

The Island of Saint Martin is about 8 km in length [17]. Transmission of electricity from one end to another end of the Island would not be possible at low voltage as the line loss at this voltage would be very high. So voltage needs to be stepped up, which would require a substation. Setting up a substation would increase the overall cost of the project, making it financially not feasible. A solution to this problem is to divide the Island into four different regions. Then a separate hybrid system is proposed for each of the four regions of the Island. As residents of the Island have set up houses evenly throughout the Island, so it can be said that all the four regions will have equal load and the load of 850 households, commercial loads are divided equally among each of the four regions.

The total load is divided into four zones according to their population and size of the area which has illustrated in Figure 2.

- Load Zone 1: West zone (Pashim Para)
- Load Zone 2: East zone (Purba Para) (Most priority load zone)
- Load Zone 3: Middle zone (Mazer Para)
- Load Zone 4: South zone (Dakshin Para)

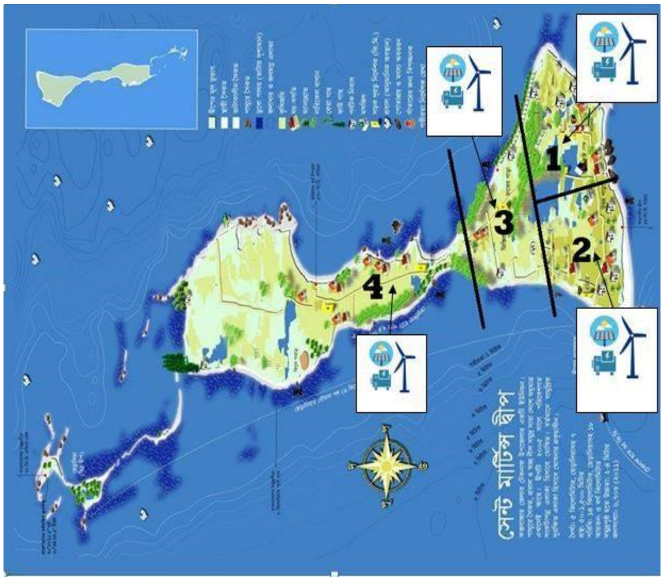
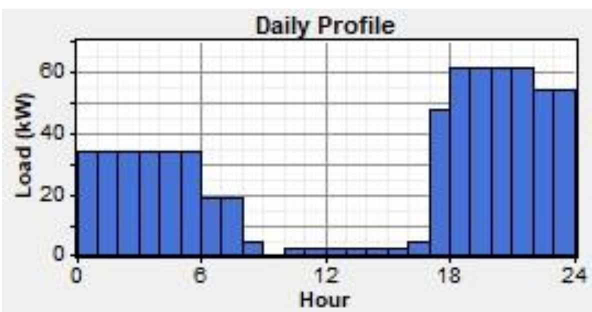
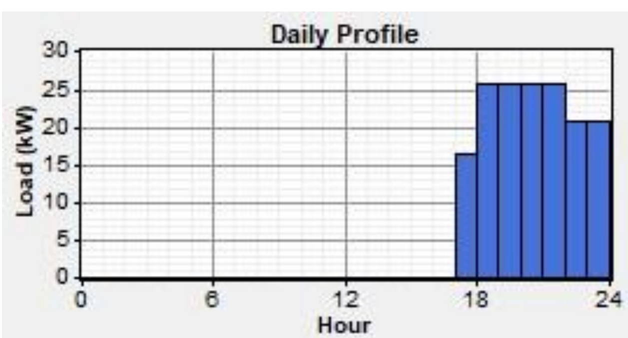


Figure 2: Dividing the Island into four zones.

For each region of the Island, the load profile will be four times lesser than the total load profile. So the load profile for each region for both the summer and winter months are shown in Figure 3a and 3b.



(a) Load profile for each region during summer.



(b) Load profile for each region during winter.

Figure 3: Load profile for each region during summer and winter.

V. MODELING OF THE HYBRID SYSTEM

Solar and wind, these two renewable sources are considered in this project. The diesel generator is used as standby and battery banks are engaged in the energy system as a result of the irregular nature of the renewable sources. The diesel generator produces AC voltage whereas the PV and the wind turbine have a voltage output of DC. The bidirectional converter is used in this configuration which is used to charge the battery by changing the AC into DC. Again the batteries are used to supply AC required by the consumer load, as all loads obligatory by consumers are AC type. This section illustrates the input variables that will help to model the system. Figure 4 represents the schematic demonstration of the HOMER simulation model of the hybrid system architecture well-thought-out in this project for each region of the Island.

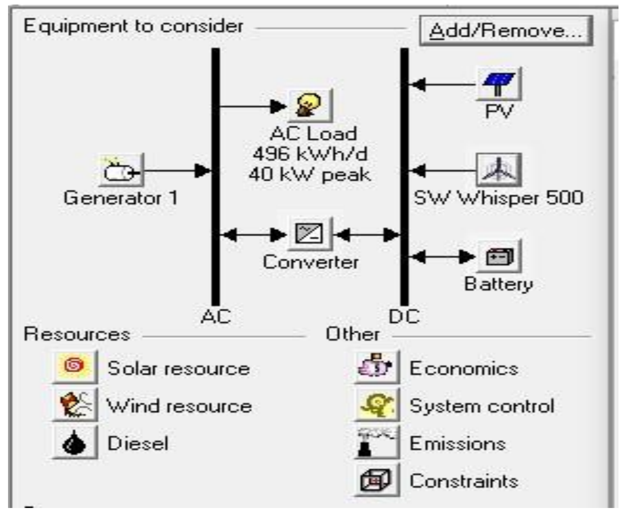


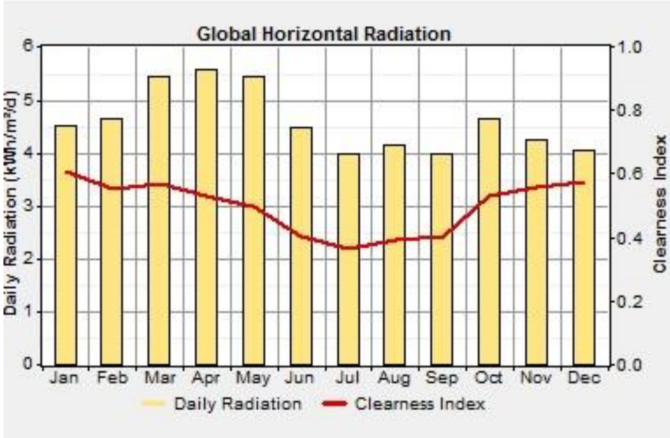
Figure 4: Architecture of the selected hybrid system produced by HOMER.

A. *Electricity Load Input :*

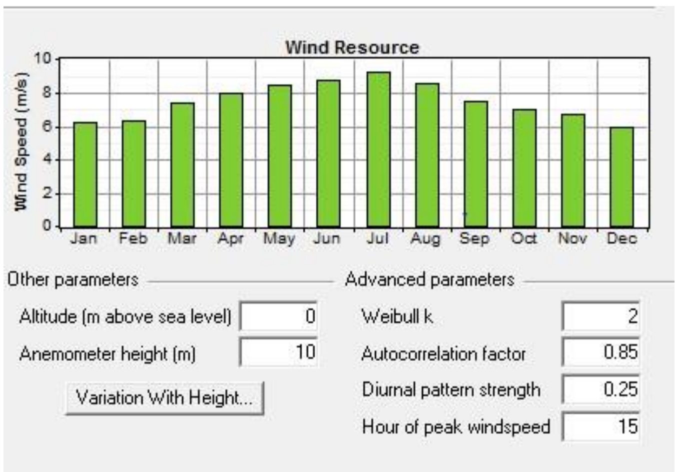
After the assortment of different modules from the library of HOMER software, the electrical load needs to be given into the software. The primary load involvement, which was finalized in section III has been given on an hourly basis. Furthermore, it also synthesizes the monthly load from the 24-hour input data. In this work, the primary electricity load termed as inputs has been considered into the following: load during summer months, i.e. from month March to November and load during winter months, i.e. from December to February.

B. Solar Energy and Wind Energy Resources in Saint Martin :

The Saint Martin Island is located in 200◦370 north and 920◦190 east. This latitude specifies the location on the Earth's surface. HOMER uses this data for computing radiation standards from clearness indices, and vice versa. The average data of daily radiation were given as input [18]. HOMER calculates the clearance index automatically from the daily radiation values which are shown in table 5.1. When the values were given as an input HOMER builds a set of 8760 hourly solar radiation value. HOMER creates the synthesized values using Graham Algorithm [18]. Figure 5a shows that the solar radiation of a year. The average annual clearness index is 0.489 and the average daily radiation is to 4.59 kWh/m2/d. On the other hand, monthly average wind speed data has shown in Figure 5b.



(a) Monthly average solar radiation data.



(b) Monthly average wind speed data.

Figure 5: Monthly average solar radiation and wind speed in Saint Martin Island.

C. Cost Modeling:

1) Capital Cost (CC): The one-time expenditures related with a development, together with the expense of procured assets such as land, apparatus, or supplementary deliveries, and the price of going into debt or issuing stock to fund the project.

2) Replacement Cost (RC): An accounting practice in which liabilities and assets are noted down on a balance sheet permitting to the cost of replacing them, rather than the original amount spent on the liabilities or assets.

3) Operation & Maintenance Cost (OMC): The Operation and Maintenance (O&M) cost of a Component is the cost associated with operating and maintaining that Component. For example, for a generator, we enter the O&M cost as an hourly value, and HOMER multiplies that by the operating hours per year to calculate the annual O&M cost.

4) Salvage (S): Salvage value is the value leftover in a component of the power system at the expiration of the project period. HOMER computes salvage value via the following equation:

$$S = C_{rep}\left(\frac{R_{rem}}{R_{comp}}\right) \tag{1}$$

R_{rem}, the residual life of the component at the termination of the project lifespan, is given by

$$R_{rem} = R_{comp}\left(R_{proj} - R_{rep}\right) \tag{2}$$

R_{rep}, the replacement cost is given by:

$$R_{rep} = R_{comp}INT\left(\frac{R_{proj}}{R_{comp}}\right) \tag{3}$$

Where, C_{rep} is the replacement cost [\$], R_{comp} component lifetime [yr], R_{proj} is the project lifetime [yr], INT is a function that returns the integer amount of a real number; for example, INT (6.843) = 6.

5) Net Present Cost (NPC): HOMER is the optimization software employed in this study to examine the optimal hybrid (i.e. PV/DG and PV-Grid) power system that satisfies user-specified constraints with the lowest net present cost (NPC) including the capital costs (CC), replacement costs (RC), O&M costs (OMC), fuel costs (FC), and salvage value (S) within the project duration. The NPC is computed as follows [61]:

$$NPC = \frac{TAC}{CRF} = CC + RC + OMC - FC - S \tag{4}$$

Total annualized cost (TAC) value and capital recovery factor (CRF) is described as follows:

$$TAC = TAC_{CC} + TAC_{RC} + TAC_{OMC} \tag{5}$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{6}$$

Where, N is the project duration and i is the yearly real interest rate. The salvage value is typically calculated at the end of the project lifespan and applies to components that have longer lifetimes than the project lifecycle.

$$S = rep\left(\frac{rem}{comp}\right) \tag{7}$$

Where, rep, rem and comp are the replacement cost of the component, the remaining lifetime and the lifetime of the component respectively.

6) Cost Data and Size Specifications of Each Component in Homer Software : The major components of the hybrid energy system are PV panels, wind turbines, 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 to simulate the system.

TABLE VIII: Price & Characteristics of PV Module

Parameters	Values
Size (KW)	1
Capital(USD)*	1000
Replacement Cost (USD)	1000
Operation and maintenance cost (USD/year)	10
Derating Factor	90%
Ground Reflection	20%
Tracking System	Two-axis

7) Solar Photovoltaic: The capital cost of the PV module is well-thought-out as BDT 75000 which includes the cost of installation and cost of charge controllers and other associative components used in PV array. The cost of solar cells per watt is BDT 65 and BDT 10/watt is needed for installation, charge controllers, and other equipment. Table VIII demonstrates the price list.

*1 USD = 85 BDT.

8) Wind Turbine: The cost of wind turbines depends on tower height and technology used. The wind turbine that has been chosen is SW Whisper 500. The turbine has the rated power of 3 kW DC. Besides, the lifetime of the turbine is 20 years. The hub height is 25 meters. The investment cost is USD 1800 with the substitution cost is considered as the same price as capital cost. The O&M cost is USD 5/year. The technical data of the wind turbine is shown in Table IX. The power curve of that wind turbine is given in Figure 6.

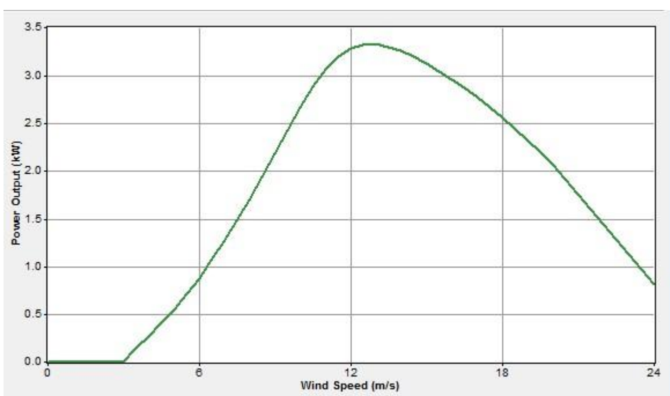


Figure 6: Power Curve of SW Whisper 500

TABLE IX: Price & Characteristics of Wind Turbine

Parameters	Values
Quantity	1
Capital (USD)	1800
Replacement (USD)	1800
Operation and maintenance cost (USD)	5
Lifetime (Years)	20
Hub height(m)	25
Power rated(KW)	3
Rotor Diameter (m)	4.5

9) Diesel Generators: The fuel used in HOMER is demonstrated by a linear curve characterized by a slope and intercept at no load. For a capacity range of 15 kW to 45 kW, the slope and the intercept are 0.25 l/h/kW and 0.08 l/h/kW respectively [17]. A diesel generator of 1 kW rated power with technical and economic parameters furnished in Table X.

10) Battery and Converter: The "Trojan L16P" storage batteries are used in the hybrid system. The specifications similar to a lifetime, efficiency, rectifier capacity efficiency, capital, and replacement cost are shown in Table XI.

TABLE X: Price & Parameters of Diesel Generator

Parameters	Values
Capital (USD)	660/KW
Replacement (USD)	660/KW
Operation and maintenance cost (USD)	0.050/hr
Operation Lifetime	30,000 Hours
Minimum Load Ratio	30%
Fuel curve intercept	0.081 l/h/kW rated
Fuel curve slope	0.25 l/h/kW output

TABLE XI: Price & Parameters of Trojan L16P Batteries

Parameters	Values
Nominal voltage	6 volt
Nominal capacity	360 Ah (2,16 kW h)
Maximum charge current	18 A
Capital cost (USD)	300
Replacement cost (USD)	300
Operation and maintenance cost (USD)	10.00/ yr

A converter is required to convert AC-DC or DC-AC. Converter should be chosen assuring its maximum lifetime and high rectifying efficiency for the hybrid system which is shown in Table XII.

TABLE XII: Price & Parameters of Converter

Parameters	Values
Capital (USD)	400
Replacement (USD)	400
Operation and maintenance cost (USD)	10 /yr
Lifetime (Years)	15
Efficiency	95%
Rectifier Capacity	100%
Rectifier efficiency	85%

VI. RESULTS AND DISCUSSION

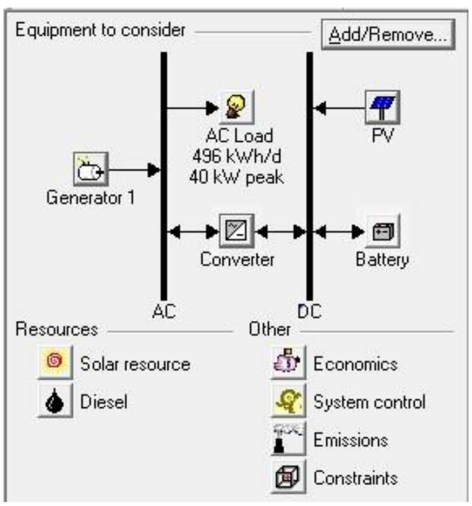
This section discussed the details of the result for the combination of a selection of hybrid power systems for Saint Martin Island. The system is designed with the help of HOMER. After familiarizing all of the input variables into the modeling tool, the software is run repeatedly to get the results. The simulation results are presented in ascending order of net present cost (NPC) from top to bottom. Moreover, the cost of energy (COE) and the cost of operation could be used for the ranking of power generating schemes to get the best renewable-based hybrid combination.

A. System design:

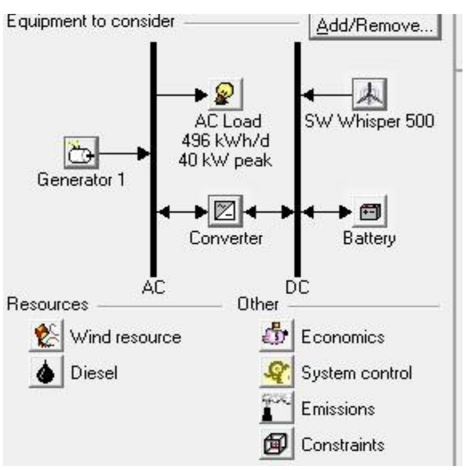
HOMER simulates different configurations of energy system components. The complexity and computation time are affected by the number of parameters and the total number of potential values involved in the design. In this section, four different scenarios are proposed for further analysis. They are:

- Solar PV - Diesel Generator - Battery bank (Scenario A)
- Wind Turbine - Diesel Generator - Battery bank (Scenario B)
- Solar PV - Wind Turbine - Diesel Generator (Scenario C)
- Solar PV - Wind Turbine - Diesel Generator - Battery bank (Scenario D)

A Hybrid system (scenarios) with less NPC, less COE, and less operating cost would be suggested in our chosen system. From the simulation result, the suggested scenarios based on the same datum values are to be compared using the same variable cases in terms of techno-economic aspects from among the least cost results. The detailed specification of each component along with load requirement is presented in Figure 7 and Figure 8

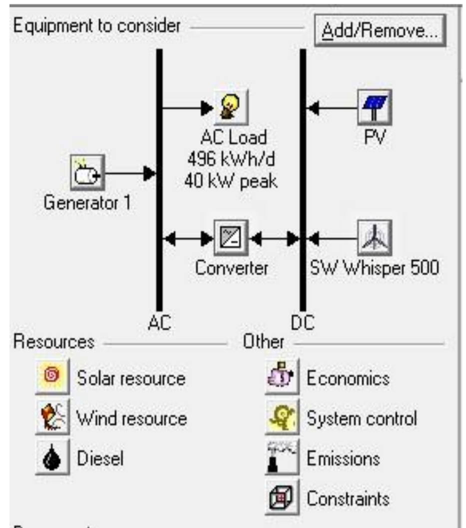


(a)

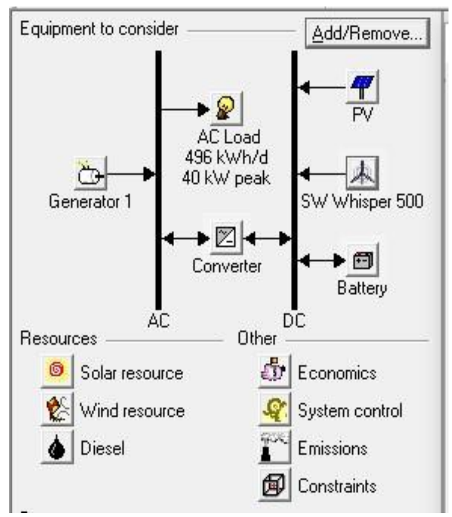


(b)

Figure 7: Design optimization of HRES (a) scenario A (PV- Diesel Generator-Battery bank) (b) scenario B (Wind-Diesel Generator Battery bank)



(a)



(b)

Figure 8: Design optimization of HRES (c) scenario C (Wind-PV-Diesel Generator) (d) scenario D (Wind-PV-Diesel Generator-Battery Bank)

B. Comparison of Scenarios :

The cost-effective system in the form of categorized simulation result is displayed in table XIII ranked in the order of least NPC. Scenario comparison was performed keeping the constraint values constant for all system configurations. The best energy system was selected with less net present cost (NPC), less cost of energy (COE), and less cost of operation.

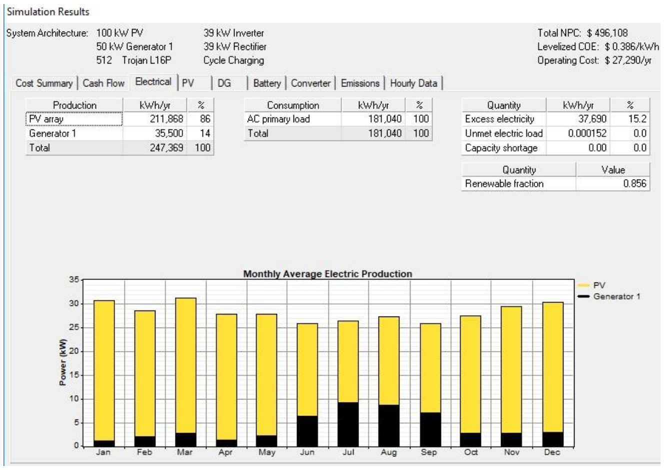
(Scenario A): Solar PV - Diesel Generator-Battery bank Figures 9a and 9b.

(Scenario B): Wind Turbine- Diesel Generator-Battery bank Figures 10a and 10b.

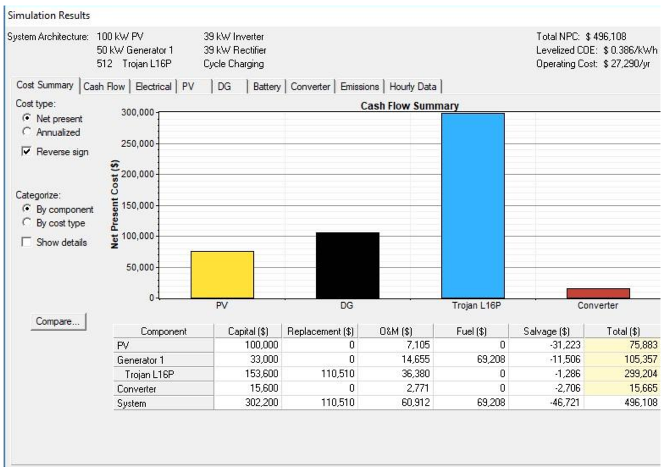
(Scenario C): Solar PV – Wind Turbine – Diesel Generator Figure 11a and 11b.

(Scenario D): Solar PV-Wind Turbine-Diesel Generator-Battery bank Figures 12a and 12b.

1) Based on Total Net Present Cost: Referring to Table XIII and Figure 13a, NPC of scenario D is least among all the scenarios, with USD 250,919. Scenario A has the next least NPC with USD 496,108. The other scenarios (C, B) are ranked in the order of increasing NPC. Hence, in terms of NPC, D is the best choice among all the other scenarios

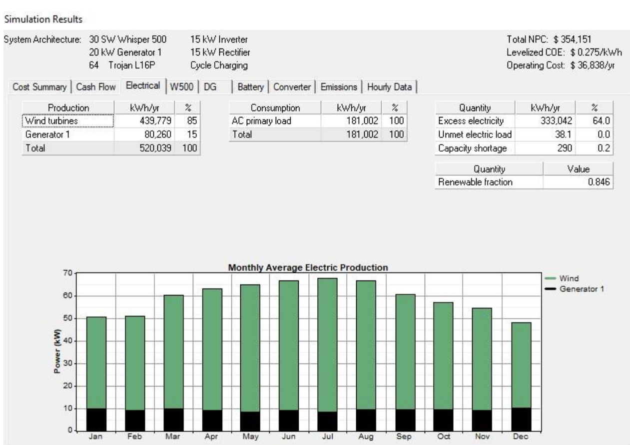


(a) Electrical parameters and simulation results

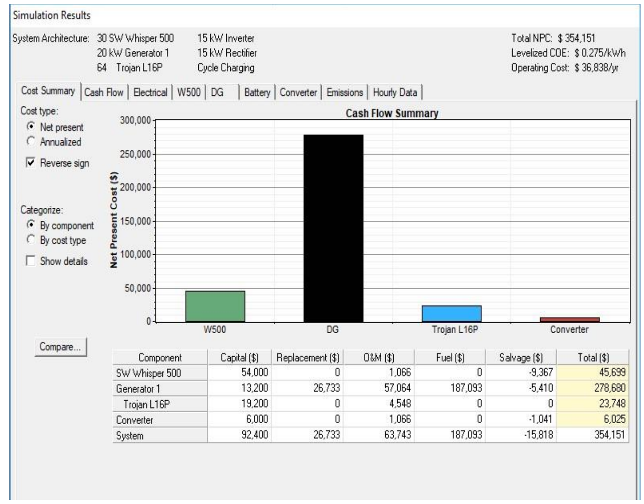


(b) Cash flow summery

Figure 9: Electrical parameters with simulation and Cash flow summery of Scenario A (PV-Diesel generator-Battery bank).



(a) Electrical parameters and simulation results



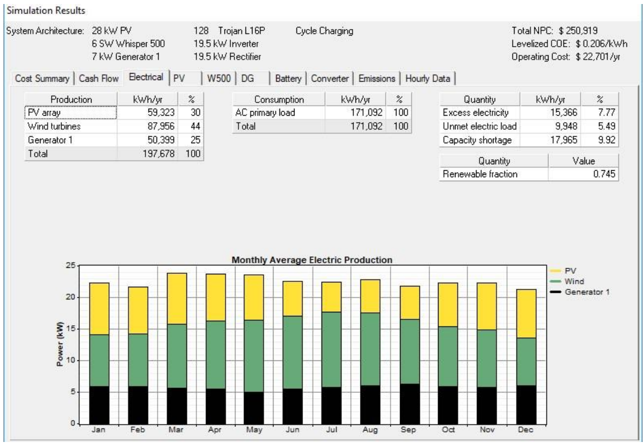
(b) Cash flow summery

Figure 10: Electrical parameters with simulation and Cash flow summery of Scenario B (Wind Turbine- Diesel Generator-Battery bank).

(a) Electrical parameters and simulation results

(b) Cash flow summery

Figure 11: Electrical parameters with simulation and Cash flow summery of Scenario C (Solar PV – Wind Turbine–Diesel Generator).



(a) Electrical parameters and simulation results.

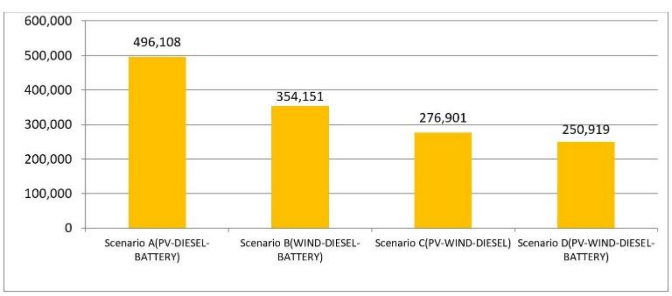
(b) Cash flow summery

Figure. 12: Electrical parameters with simulation and Cash flow summery of Scenario D (Solar PV-Wind Turbine-Diesel Generator Battery bank).

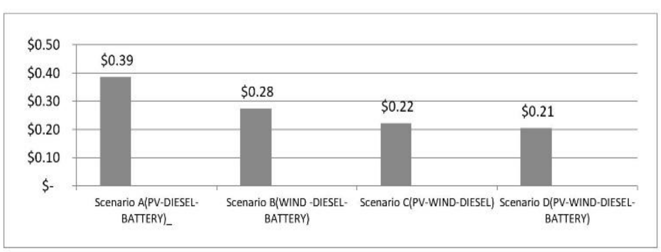
TABLE XIII: Comparison of 4 Scenarios

Scenario	PV	Wind	Gen	Battery	Conv (kW)	Initial Capital	Operating Cost($/yr)	Total NPC ($/yr)	COE ($/kWh)	Ren. Frac.
A	100		50	512	39	302,200	33,290	496,108	0.386	0.856
B		30	20	64	15	92,400	36,838	354,151	0.275	0.846
C	25	8	17		28	61,820	30,270	276,901	0.223	0.707
D	28	6	7	128	19.5	89,620	22,701	250,919	0.206	0.745

2) Based on Cost of Energy: Detail information of the least cost of energy (COE) for each hybrid system configurations (scenarios) can be found in Figure 13b. Scenario D has the least COE. Three scenarios (scenario A, scenario B, and scenario C) have almost the same COE with a small difference. For scenario D the COE is around 0.21$/kWh, for scenario A it is about 0.39$/kWh, for scenario B it is 0.28$/kWh, for scenario C it is 0.22$/kWh. Taking this parameter as a basis for comparison benchmark, scenario D is the best option among all four different hybrid systems.



(a) Comparison of scenarios based on NPC



(b) Comparison of scenarios based on COE

Figure. 13: Comparison of scenarios based on NPC and COE respectively

3) Based on Cost of Operation: The third comparison criterion is the cost of operation per year which has illustrated in Figure 14. Scenario D has the least cost of operation per year of 22,701$/yr. Scenario A has the cost of operations per year with 33,290$/yr. and Scenario C has the cost of operations per year with 30,270$/yr. And for scenario B the cost of operation is much more expensive. So considering these, scenario D is selected, as it has the least cost of operations among all the hybrid systems.

Among all scenarios, one system architecture needs to be selected. According to all the previously mentioned benchmarks, scenario D is found to be the best option. It has the least NPC, at least COE, and also the least cost of operation. Scenario D is the best hybrid configuration among all possible combinations. The selected scenario (scenario D) which includes a PV-wind-diesel generator is discussed in the next subsections.

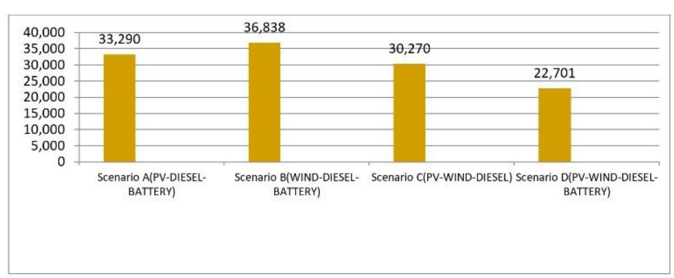


Figure. 14: Comparison of scenarios based on the cost of operation

C. Most Feasible solution for Saint Martin Island:

Solar PV-Wind-Diesel Hybrid configuration is the most feasible solution for Saint Martin Island. This decision has been come out by considering the following facts:

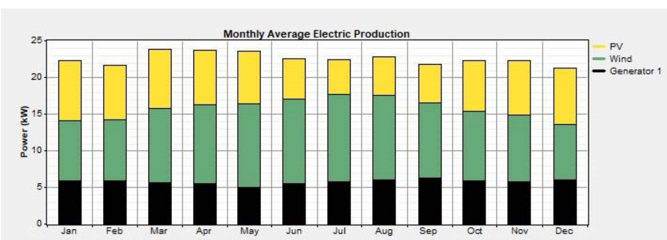
- Least Cost of Energy & least Net present cost.
- Incorporated with maximum sources.
- Peak load can be easily compensated.
- High renewable fraction (74.5%).
- Least CO2 emission.
- Can be extended in the future.
- Requires less space if PV is decentralized.

D. Analysis of the Selected Scenario:

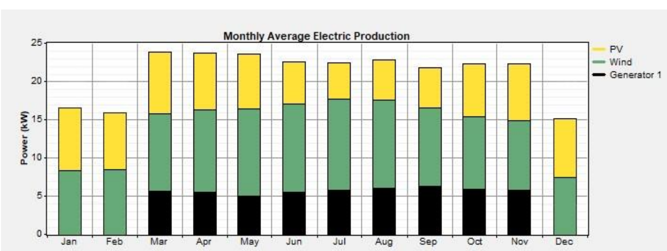
The selected hybrid system consists of 28 kW photovoltaic panels, 6 pieces 3 kW Wind Turbines, 7 kW diesel generator, 128 batteries, and a 19.5 kW converter. The trend of monthly electricity production in kW obtained after the simulation is shown in Figure 15a. Solar irradiation during June, July, and August are the least, so the percentage of electricity generated from PV is least in these months Similarly, diesel generator run regularly during the summer months to meet the large night time load, as the charge stored in the battery through the PV is not adequate to meet the full load requirement during night time.

In winter the power consumption is 169.03 kWh/day in each region which is very low comparing the power consumption in summer.

So, we have decided to stop operating all the diesel generators in winter which has illustrated in Figure 15b.



(a) Electric Production. (With diesel generator in winter)



(b) Electric Production. (Without diesel generator in winter)

Figure 15: Monthly Average Electric Production. (With and Without diesel generator in winter)

Thus we get the total power generated from PV and wind turbine is=378.399 kWh/day in each region. Required power generation is 169.036 kWh/day. So, the excess power generation will be= 209.36kWh/day, which can be used for other purposes. The electricity generated by individual power units of the selected hybrid system is shown in Figure 16. PV array power production accounts for 32% (59,323 kWh/year), wind turbines account for 48% (87,956kWh/year) and diesel generator accounts for 20% (37,368 kWh/year) of total electricity produced by the hybrid system.

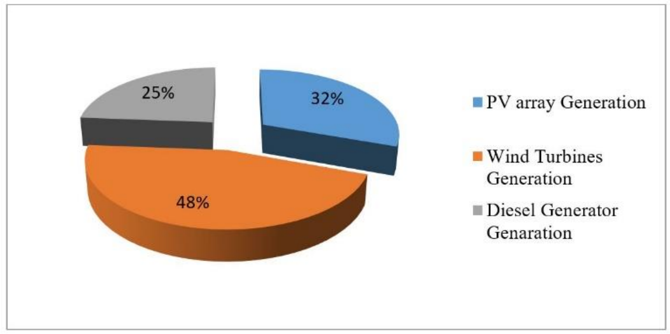


Figure 16: Power generation percentage share from each component.

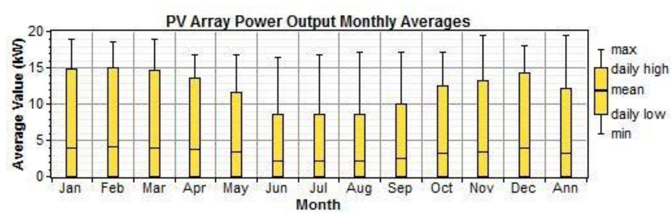
Figure 17a shows the share of electricity generation via solar PV. As noticed from the figure, electricity generation is highest during January, February, and March, months with the highest solar radiation striking the earth's surface. Starting from June till the end of August PV power generation is lower than the other months due to cloud coverage of the sky. Table XIV shows the PV scheme simulation result.

TABLE XIV: PV scheme simulation result

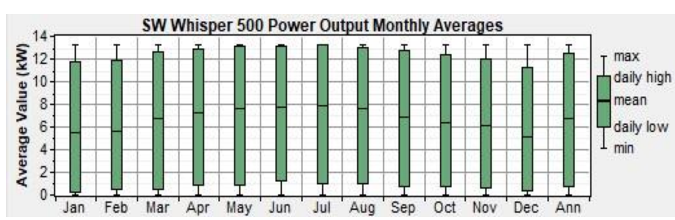
Quantity	Values	Units
Rated Capacity	28	kW
Mean Output	168	kW/day
Hours of Operation	4,402	Hr/yr
Levelized Cost of Energy	0.0504	$/kWh

The mean power output of PV is about168kWh/day. The rated power output is 28kWp when the sky is clear. Solar PV's total hour of operation is 4,402 hours annually. Levelized cost of electricity for this system is 0.0504$/kWh.

Figure 17b shows the share of electricity generation via a wind turbine. As noticed from the figure, electricity generation is highest during the months' May, June, July, and August months with highest wind speed remains in Saint Martin. Table XV shows the wind turbine simulation result.



(a) PV array power output



(b) SW Whisper 500 power output

Figure 17: Monthly Average PV array power output and SW Whisper 500 power output respectively.

The mean power output of Wind Turbine is about 10kWh/day. The rated power output is 18 kW when wind speed is good. Wind turbine total hour of operation is 7,954 hours annually. Levelized cost of electricity for this system is 0.0146$/kWh.

TABLE XV: Wind Turbine Simulation Result

Quantity	Values	Units
Rated Capacity	18	kW
Mean Output	10	kWh
Hours of Operation	7,954	Hr/yr
Levelized Cost of Energy	0.0146	$/kWh

System load variation and continuous running of a diesel generator at lower load depict poor diesel engine performance. Diesel generator power production and the simulation result is shown in Table XVI. The total annual hour of operation is 6,624 hours with a generator operational lifetime of 3.11 years. Total electrical production per year is 37,368 kWh/year and the mean electrical output is 5.77 kW. Table XVI shows the diesel generator simulation result.

TABLE XVI: Diesel generator simulation result.

Quantity	Values	Units
Electrical Production	37,368	kW/yr
Mean Electrical Output	5.77	kW
Hours of Operation	6,624	Hr/yr
Operational Life Time	3.11	Yr

Due to the operation of diesel generators, carbon dioxide and other gases are released. This emission of carbon dioxide gas is the main contributor to the greenhouse effect. So the less the amount of this gas that can be released, the better it is for the environment. Figure 18 illustrates the amount of carbon dioxide and other pollutant gas released per year. The total amount of carbon dioxide released per year by the proposed system is 45,028 kg. The system also releases other pollutant gases of 1214.028 kg per year. The amount of released gas is far less than the gas released if the total electrical load was supplied by only diesel generators.

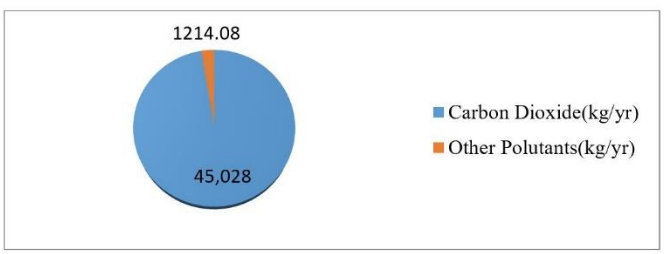


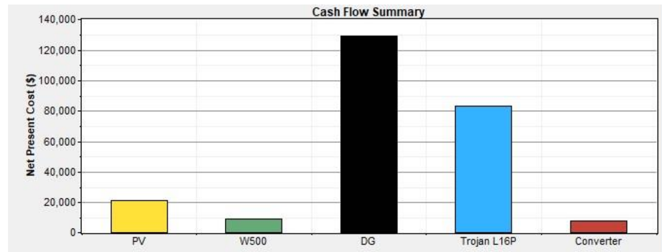
Figure 18: Pollutants emitted to the environment

E. Cost Summary:

Out of all the components, diesel generator draws the most expensive in the whole project lifetime. The total NPC of the diesel generator is USD 129,277. The initial cost of diesel generator has incurred low cost to purchase, however due to the higher cost of fuel, the most expensive cost draws from this component of the hybrid system. The battery comes second in terms of NPC of USD 83,422 followed by solar PV cost of USD 21,247, a converter with USD 7,833, and a wind turbine with USD 9,140. The power system capital cost, NPC and the components capital cost is presented in Figure 19 and 20

F. Payback Calculation:

Payback deliberates the preliminary asset costs and the resulting annual cash flow. The payback period is usually calculated by the amount of time (usually measured in years) to pull through the original asset. The payback scheme doesn't account for savings that may continue from a project after the initial investment is paid back from the profits of the project, but this method is helpful for a "first-cut" analysis of a project. Here we have to consider 20.955 taka or $0.25 per kW hour.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	28,000	0	1,990	0	-8,742	21,247
SW Whisper 500	10,800	0	213	0	-1,873	9,140
Generator 1	4,620	9,359	19,987	97,199	-1,888	129,277
Trojan L16P	38,400	50,432	9,095	0	-14,506	83,422
Converter	7,800	0	1,386	0	-1,353	7,833
System	89,620	59,791	32,671	97,199	-28,362	250,919

Figure 19: Cash flow summary in terms of NPC by component type.

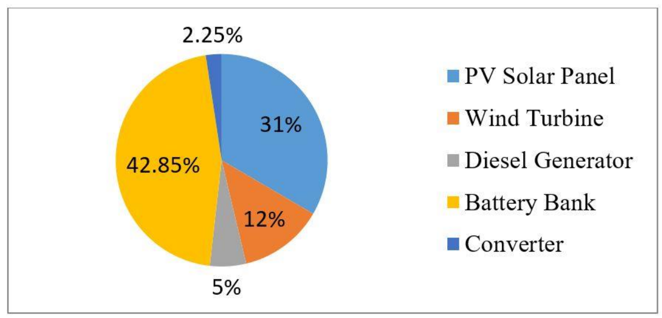


Figure 20: Capital cost percentage by components

Considering 1kWh = 20.955Tk or $0.25, Capital cost of the Hybrid system = $80,500 where the capital money will be lent with 6% interest.

As a result, the total capital cost with 6% interest = $85330

So, the annual income = $45908 [As annual consumption of electricity = 183,631 kWh]

So, payback period= $\frac{85330}{45908}$ = 1.85 years ≈ 2 years

If an investor invests in this project, he can make up his capital within 2 years. As the project lifetime is 25 years, it can make a profit for the rest of 23 years.

VII CONCLUSION

The main aim of this work is to propose a renewable energy-focused hybrid supply system for powering Saint Martin Island, an off-grid site in Bangladesh. In this work, locally available solar and wind resources are being considered as a primary energy source to build a sustainable and reliable supply system. Bangladesh being a tropical country is blessed with substantial irradiance all year round. Throughout summer, while solar radiation is plentiful with slight wind energy, the solar PV system can supply a maximum of the essential energy. In the winter season, when wind speeds are advanced with less solar radiation, the wind turbines will supply most of the requirement of energy. This indicates a complementary relationship between the two sources in this case. For ensuring the energy sustainability the Island is divided into four regions and for each region, a hybrid power system is proposed. Numerical results demonstrate that the hybrid solar PV/WT system has enough potential to fulfill the load requirement of Saint Martin Island. Moreover, the diesel generator and storage device can provide sufficient backup power during the shortage or outage of renewable energy. To the end, the hybrid system could produce electricity at USD 0.206/kWh which is much less than the amount per unit cost the residents of the Island have to pay at the moment.

Conflicts of Interest: The authors declare no conflicts of interest.

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