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Techno-Economic Analysis of a Solar PV-Fuel Cell based Hybrid Energy System for St. Martin Island Using HOMER

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Abstract: Conventional resources is limited for our planet. So renewable sources is the only hope to us for supply energy consistently in future. However the energy crisis has started in many developing countries like Bangladesh. Renewable sources system as Solar PV coupled with diesel and Hydrogen based energy generation system is a most reliable and cost effective arrangement for our country where exists not only the energy problem but also there is a lack of some expectable renewable resources like wind speed, geothermal energy etc. So PV-Diesel-Fuel Cell hybrid system is considered for the energy system in remote areas of Bangladesh. In this study St. Martin has been taken for the discussion of the cost minimization analysis, load profile and variation of solar irradiance, GHG emissions of a hybrid energy generation system. This hybrid system is combined with solar PV, fuel Cell and diesel generator. Here, HOMER is used to examine the most cost effective configurations among a set of systems for electricity requirement of 80 KWh/day primary load with 14 kW peak load.

Keywords: *Conventional Resources, Hybrid Generation System, Electrolyzer, Hydrogen Tank, Solar PV, Diesel, GHG, HOMER.*

I. Introduction

Bangladesh is situated between 20°34' and 26°38' north latitudes and 88°01' and 92°41' east longitudes and the coastal area in the southern part of Bangladesh has a huge potential of establishing solar power generation. St. Martin island a scenic sea beach on the south of Bangladesh situated at 20°37' north latitudes, 92°19' east longitudes, about 9 km south of the tip of the Cox's Bazar-Teknaf peninsula, and forming the southernmost part of Bangladesh.. The total population of this island 6000. The most important attraction of the beach is that one can see dazzling view of sunset from its locations. Other attractions at St. Martins island include blue sky, huge expanse of water, the evergreen forest in surrounding areas, rows of coconut trees, boats of many different kinds and their colorful sails, and surfing waves. For these attractive scenarios St. Martins has become a popular tourist spot due to its natural beauty. Since the island is far away from the main land grid connection is almost impossible in terms of cost and geographic location an off-grid hybrid energy system can be launched to meet energy demand of this coastal area. However, the electricity demand is partly fulfilled by standalone diesel generators. The solar irradiation is 4.549kWh/m^2/day which is suitable for setting up solar energy system (R. Amin *et al.*, 2014).

A number of research work has been conducted for electrification of different coastal and rural areas of Bangladesh. They have proposed different types of energy solutions to meet a fixed demand. An optimized model with Solar PV-Wind-Diesel system has been proposed for Saint-Martin Island in (A.K.M. Sadrul *et al.*, 2012). A feasibility study of a Solar PV-Biogas-Battery hybrid energy system has been simulated in HOMER (A. Islam *et al.*, 2015). A detailed renewable energy prospect of Bangladesh has been illustrated in (N.R. Chodhury *et al.*, 2012). Technical and economic analysis of a hybrid energy system using HOMER has been published in (Hrayshat. ES *et al.*, 2009). A paper presented an optimized energy system model for a small locality in Kutubdia Island (S. Salehin *et al.*, 2016). So a bunch of researchers are continuing their research activity to find an energy efficient solution for isolated area electrification of Bangladesh. In that context, I have proposed a new energy solution for Saint Martin Area to meet the fixed energy demand. In this paper, a technical and economic analysis has been described and the simulation has been done in HOMER platform.

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II. Research Methodology using HOMER

In this work, techno-economic analysis of a standalone PV-Fuel cell based hybrid system is proposed for a coastal area electrification of Bangladesh. This system design can be applied other parts like rural areas, hilly areas where grid connection is absent. At first, most suitable energy resources are selected (solar irradiance) for planning a hybrid energy system. Then hybrid energy system is designed by using the best suitable resources. For the techno-economic analysis and sizing of different components of the system the optimization software HOMER (Hybrid Optimization Model for Electric Renewables) is simulated. HOMER performs a bunch of simulation for each system configuration that can be considered. The system cost calculations are done studied which account costs such as capital, replacement, operation and maintenance, fuel, and interest. To determine the feasibility of the proposed system, this economic analysis is a significant task of this work. Comparison with solar photovoltaic (PV) based other energy systems and diesel based energy system is studied for confirm in the acceptability of the proposed system. Moreover, HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER analyze the electric and thermal demand in the hour to the energy that the system can supply, and calculates the flows of energy among the component of the system. For systems that include batteries or fuel-powered generators. HOMER also estimate a energy management profile to operate the generators and whether to charge or discharge the batteries. Finally HOMER figure out a list of energy solutions, sorted by net present cost (sometimes called lifecycle cost), that can be used to compare system design options.

III. Load Demand and Renewable Energy Resource Assessment

The primary condition to propose an energy solution is fulfillment of energy demand of a specific area. Moreover, renewable resources is also be assessed if there is any exists.

III.A Load Demand

A group of community of 100 households and 10 shops has been considered. The proposed usable load pattern has given in Table 1.

Table 1: Proposed Load Pattern for Hybrid System

Items	Households		Shops	
	Qty	Watt	Qty	Watt
CFL Bulb	3	15	2	15
Celling Fan	1	40	1	40
Television	1	40	-	40
Refrigerator		-	1	150

Figure 1 and Figure 2 shows two load profiles for 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 13 kW and primary load to 76.5 kWh/day.

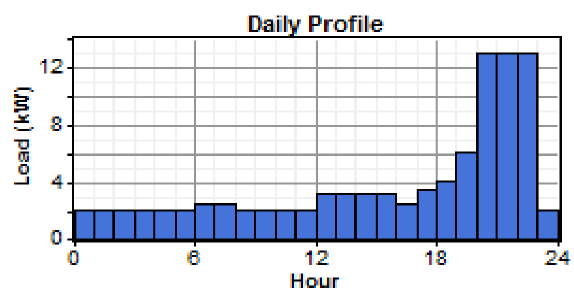


Figure 1: Daily Load Profile in winter at St. island

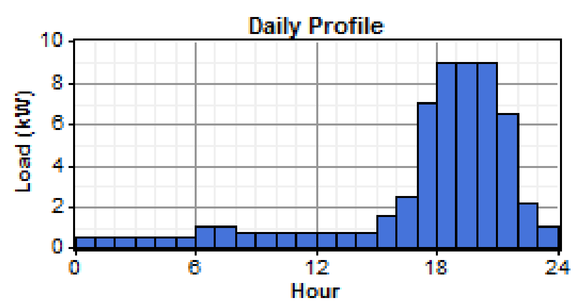


Figure 2: Daily Load Profile in summer at St. island

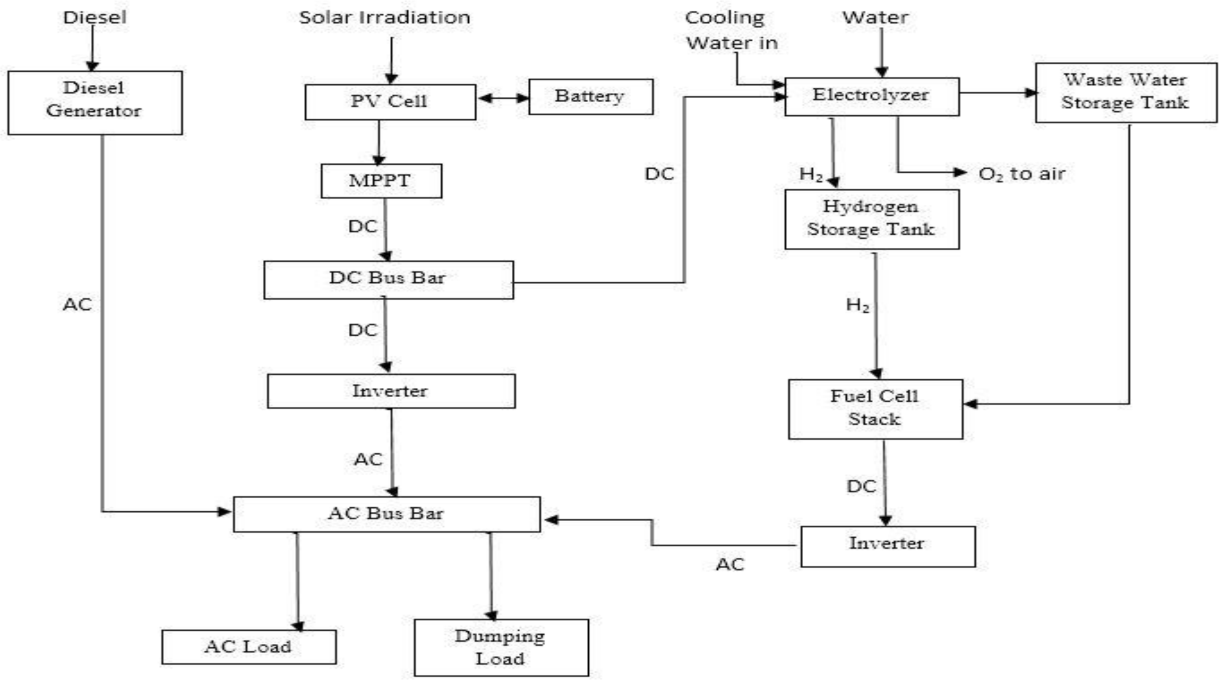


Figure 4: Block Diagram of Proposed Solar PV-Fuel Cell based Micro Grid System

III.B Solar Irradiance Profile

A monthly averaged global radiation data has been taken from NASA (National Aeronautics and Space Administration), which has shown in (NASA web *et al.*, 2018). 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 3 illustrates that the solar radiation is high from February to April. The average annual clearness index is 0.484 and the average daily radiation is 4.549 kWh/m^2/d.

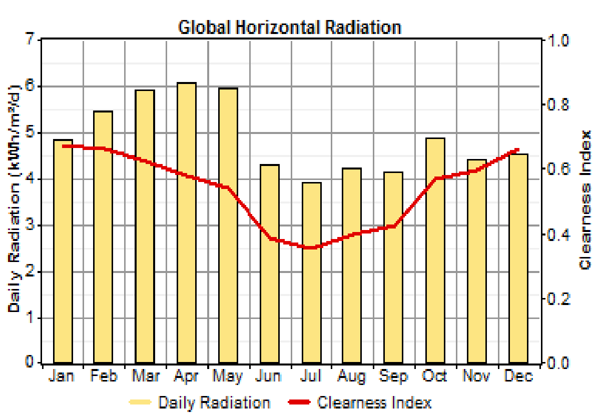


Figure 3: Solar Irradiation throughout the year at St Martin

IV. Proposed Hybrid System Model

The proposed hybrid energy generation system consists of PV panels, diesel generators, batteries and converters are shown in Figure 4.

IV.A Solar PV Panels

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. 25 kW to 45 kW PV modules are considered. The parameters considered for the simulation solar PV (1 US$ = 78 BDT) are furnished in Table 2.

Table 2: Solar Panel Specifications

Parameter	Unit	Value
Capital Cost	BDT/W	70
Replacement Cost	BDT/W	65
Operation and Maintenance Cost	BDT/W	50
Lifetime	Year	25
Deration Factor	Percent	90
Tracking System	No Tracking System	0.05

IV.B Diesel Generator

The fuel used in HOMER is modeled by a linear curve characterized by a slope and intercept at no load as shown in Fig. 5. For a capacity range of 15 kW, the slope and the intercept are 0.33 l/h/kW and 0.05 l/h/kW respectively (K. Q. Nguyen *et al.*, 2005). A diesel generator of 15 kW rated power with technical and economic parameters furnished in Table 3.

Table 3: Diesel Generator Specifications

Parameter	Unit	Value
Capital Cost	BDT/W	10000
Replacement Cost	BDT/W	8000
Operation and Maintenance Cost	BDT/W	30
Operational Lifetime	Year	15000
Minimum load ratio	Percent	10
Fuel curve intercept	l/h/KWrated	0.05
Fuel curve slope	l/h/KWoutput	0.33
Fuel Price	BDT	56

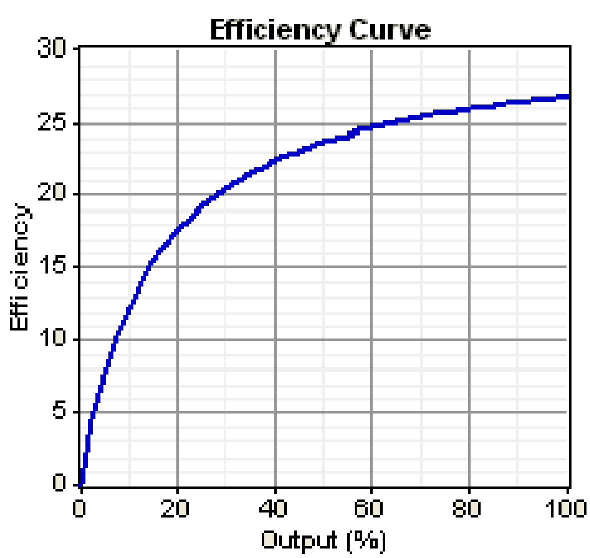


Figure. 5: Efficiency curve of a 15KW Diesel Generator.

IV.C Energy Storage Device

The Surrette 6CS25P storage batteries have been utilized in the hybrid system (M. S. Kaiser *et al.*, 2005). The technical and economic parameters (1 US$ = 78 BDT) are stated in Table 4.

Table 4: Battery Specifications

Parameter	Unit	Value
Nominal Voltage	Volt	6
Nominal Capacity	Ah	1156
Maximum Charge Current	A	41
Round trip Efficiency	%	80
Min State of Charge	%	40
Capital Cost	Tk/Kwh	10000
Replacement Cost	Tk/Kwh	10000
O&M Cost	Tk/Kwh/yr	200

IV.D Converters

Most of the house appliances are compatible for AC current nowadays. As the electricity generated from the PV or wind turbine is DC, converter is needed to change it into AC. Table 5 shows the technical and economical parameters of the converters. A 1 kW system is associated with $191 capital and $128 replacement cost (1 US$ = 78 BDT) as shown in Table 5.

Table 5: Converter Specifications

Parameter	Unit	Value
Capital Cost	BDT/Kw rated	14933
Replacement Cost	BDT/Kw rated	10000
Lifetime	Years	10
Efficiency	%	90
Rectifier efficiency	%	95
Rectifier Capacity	&	85

IV.E Electrolyzers

Currently production cost of electrolyzer is $2500-$3000 per kW. With improvements in polymer technology, control systems and power electronics, it is expected that costs would reduce much in 10 years (Dalton *et al.*, 2009). In this analysis, various sizes of electrolyzer was considered. A 1 kW system is associated with $2700 capital, $2565 replacement and $20 maintenance cost (1 US$ = 78 BDT) as in Table 6. A 3 kW diesel generator with technical and economic parameters is furnished here. Lifetime is considered as 25 years with efficiency of 85%.

Table 6: Electrolyzer specifications

Parameter	Unit	Value
Capital Cost	BDT/kW	212000
Replacement Cost	BDT/kW	200000
Operation and Maintenance Cost	BDT/kW	1560
Operational Lifetime	Year	25

IV.F Fuel Cell Stack

The cost of fuel cell varies greatly depending on type of technology, reformer, auxiliary equipment's and power converters. At present, a fuel cell cost varies from $1000-$2000 per kW (Dalton et al 2009). Here, the capital, replacement and operational costs were taken as $1100, $1100 and $0.020/h for a 1 kW system (1 Doller = 78 BDT)., respectively. Five different sizes of fuel cells were taken in the simulation process: 0 (no fuel cell used), 15, 20, 25 and 30 kW. Fuel cell lifetime and load ratio were considered to be 40,000 h and 0%, respectively.

Table 7: Fuel Cell Stack Specifications

Parameter	Unit	Value
Capital Cost	BDT/kW	85800
Replacement Cost	BDT/kW	85800
Operation and Maintenance Cost	BDT/hr	1.560
Operational Lifetime	Year	25

IV.G Hydrogen Tank

Cost of a tank with 1 kg of hydrogen capacity was assumed to be $1026 (1 US$ = 78 BDT). The replacement and operational costs were taken as $1026 and $15 year respectively.

Table 8: Hydrogen Tank Specifications

Parameter	Unit	Value
Capital Cost	BDT/kg	80000
Replacement Cost	BDT/kg	80000
Operation and Maintenance Cost	BDT/yr	1170
Operational Lifetime	Year	25

Two different sizes (5 and 10 kg) were included, to widen the search space for a cost effective configuration and the lifetime was also considered as 25 years.

IV.H Hybrid System Control Parameter

The project life has been considered as 25 years. The capacity shortage penalty is not considered. Hybrid system control parameters are shown in Tables 9-10.

Table 9: Spinning Reserve Input

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

Table 10: Contraints of HOMER Usage

Parameter	Value
Maximum un served Energy	0%
Maximum un Renewable Fraction	0 to100%

V. Results and Discussions

To evaluate the performances of different hybrid systems in this study analysis have been carried out using HOMER simulation tools which has shown in figure 6. In this software the optimized results are presented categorically for a particular set of sensitivity parameters like solar radiation, diesel price, and maximum annual capacity shortage and renewable fraction.

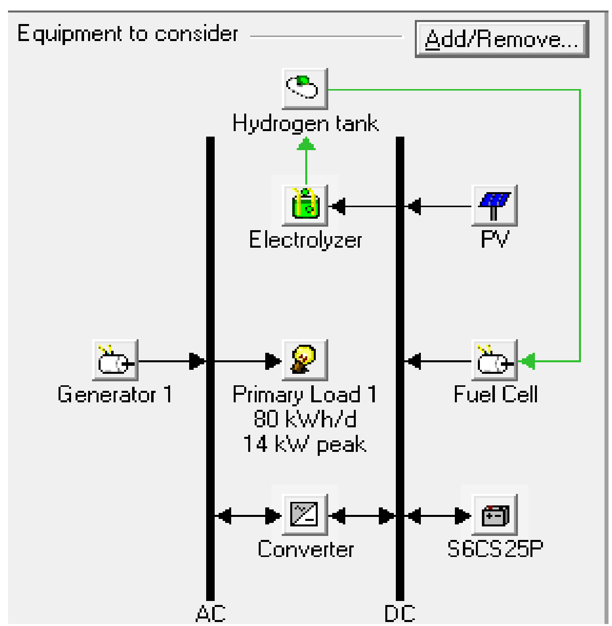
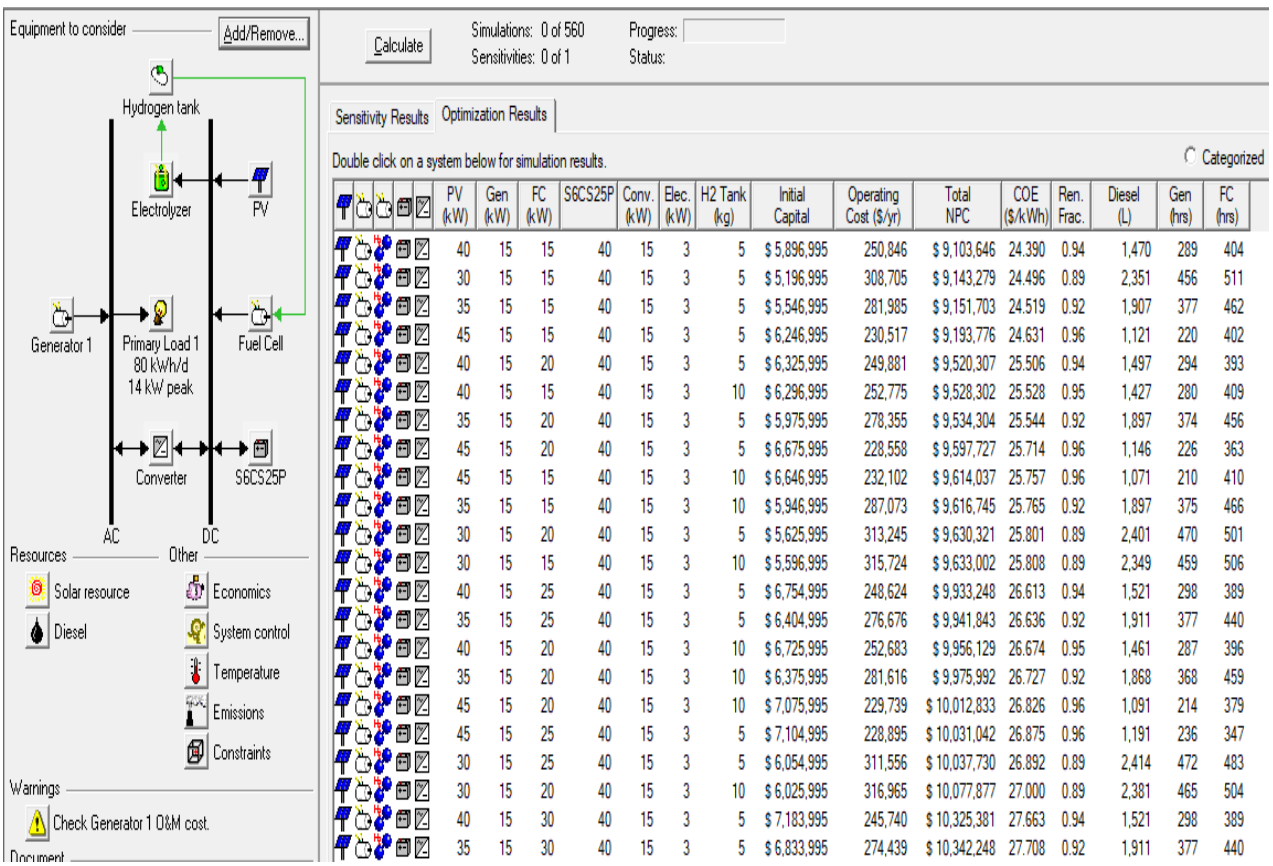


Figure 6: Proposed system implemened in HOMER

HOMER performs hundreds of hourly simulations over and over in order to design the optimum hybrid system. It is the main target to get the hybrid energy generation model which costs the least per kWh or least NPC. After thousands of simulations, HOMER shows the hybrid configurations with respect to net present cost and cost/kWh. The configuration, in this study, that gives the lowest COE of BDT (Bangladeshi Taka, Bangladeshi currency) 24.402 / KWh (USD 0.312) and lowest total net present cost (NPC) of BDT 9,108,110 (USD 116,770) with a renewable fraction 94% is configured with a 40 KW PV, a 15 KW diesel generator, a 15KW Fuel Cell generator, a 12 KW converter and 40 batteries renewable fraction, and diesel price providing more flexibility in the experiment. The optimization results for, solar irradiation 4.5486kWh/m2/d and diesel price 72 taka (0.92 $/ltr) are illustrated in Figure. 7.

It is seen that a PV, diesel generator and fuel cell based hybrid system is economically more feasible with a minimum COE and a minimum NPC. COE ($/Kwh) is lower (0.312) and optimum when using 40KW PV modules with Diesel Generators, as compared with only generator system (i.e. 1.108 $/Kwh). Renewable fraction is also greater than any other proposed model i.e. 0.945%. Total NPC is also smaller when we are



PV (kW)	Gen (kW)	FC (kW)	S6CS25P	Conv. (kW)	Elec. (kW)	H2 Tank (kg)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)	FC (hrs)
40	15	15	40	15	3	5	$ 5,896,995	250,846	$ 9,103,646	24.390	0.94	1,470	289	404
30	15	15	40	15	3	5	$ 5,196,995	308,705	$ 9,143,279	24.496	0.89	2,351	456	511
35	15	15	40	15	3	5	$ 5,546,995	281,985	$ 9,151,703	24.519	0.92	1,907	377	462
45	15	15	40	15	3	5	$ 6,246,995	230,517	$ 9,193,776	24.631	0.96	1,121	220	402
40	15	20	40	15	3	5	$ 6,325,995	249,881	$ 9,520,307	25.506	0.94	1,497	294	393
40	15	15	40	15	3	10	$ 6,296,995	252,775	$ 9,528,302	25.528	0.95	1,427	280	409
35	15	20	40	15	3	5	$ 5,975,995	278,355	$ 9,534,304	25.544	0.92	1,897	374	456
45	15	20	40	15	3	5	$ 6,675,995	228,558	$ 9,597,727	25.714	0.96	1,146	226	363
45	15	15	40	15	3	10	$ 6,646,995	232,102	$ 9,614,037	25.757	0.96	1,071	210	410
35	15	15	40	15	3	10	$ 5,946,995	287,073	$ 9,616,745	25.765	0.92	1,897	375	466
30	15	20	40	15	3	5	$ 5,625,995	313,245	$ 9,630,321	25.801	0.89	2,401	470	501
30	15	15	40	15	3	10	$ 5,596,995	315,724	$ 9,633,002	25.808	0.89	2,349	459	506
40	15	25	40	15	3	5	$ 6,754,995	248,624	$ 9,933,248	26.613	0.94	1,521	298	389
35	15	25	40	15	3	5	$ 6,404,995	276,676	$ 9,941,843	26.636	0.92	1,911	377	440
40	15	20	40	15	3	10	$ 6,725,995	252,683	$ 9,956,129	26.674	0.95	1,461	287	396
35	15	20	40	15	3	10	$ 6,375,995	281,616	$ 9,975,992	26.727	0.92	1,868	368	459
45	15	20	40	15	3	10	$ 7,075,995	229,739	$ 10,012,833	26.826	0.96	1,091	214	379
45	15	25	40	15	3	5	$ 7,104,995	228,895	$ 10,031,042	26.875	0.96	1,191	236	347
30	15	25	40	15	3	5	$ 6,054,995	311,556	$ 10,037,730	26.892	0.89	2,414	472	483
30	15	20	40	15	3	10	$ 6,025,995	316,965	$ 10,077,877	27.000	0.89	2,381	465	504
40	15	30	40	15	3	5	$ 7,183,995	245,740	$ 10,325,381	27.663	0.94	1,521	298	389
35	15	30	40	15	3	5	$ 6,833,995	274,439	$ 10,342,248	27.708	0.92	1,911	377	440

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

Figure 7: Optimization results for PV-diesel-Fuel Cell system for a solar radiation of 4.549 KWh/m^2/d compared to diesel-generator system where diesel price of 72 BDT/ L

V.A System Optimization Results

Simulations have been conducted considering different values for solar radiation, considerable using Hybrid system. Consumption of Diesel is less (1.470 L) in this case than any other proposed optimized model.

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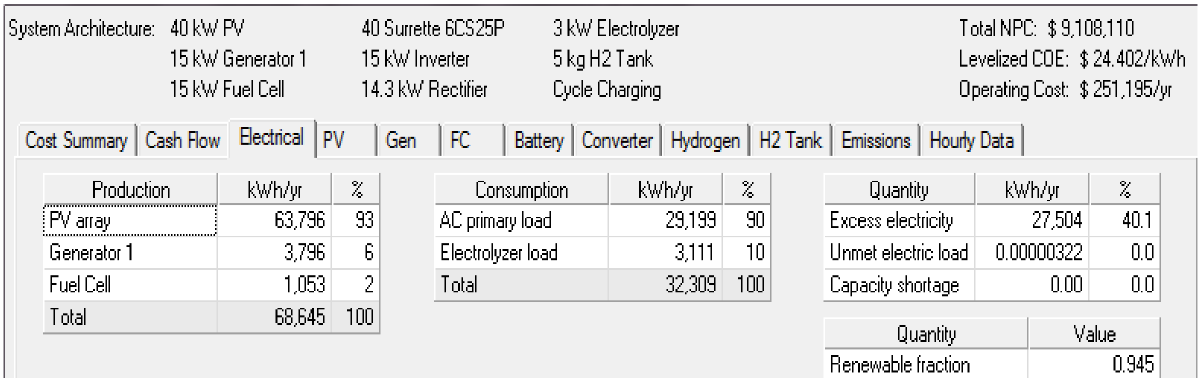

Production	kWh/yr	%
PV array	63,796	93
Generator 1	3,796	6
Fuel Cell	1,053	2
Total	68,645	100

Consumption	kWh/yr	%
AC primary load	29,199	90
Electrolyzer load	3,111	10
Total	32,309	100

Quantity	kWh/yr	%
Excess electricity	27,504	40.1
Unmet electric load	0.00000322	0.0
Capacity shortage	0.00	0.0

Quantity	Value
Renewable fraction	0.945

Figure 8: Energy Generated by PV, diesel and fuel cell system, excess electricity, un-met electric load, capacity shortage and renewable energy fraction.

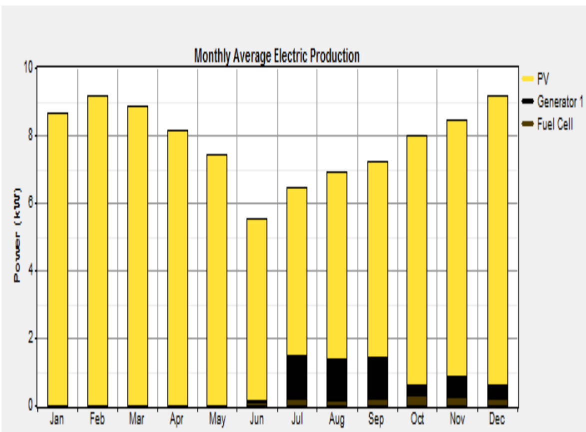

Figure 9: Electricity production profile by solar pv, diesel generator amd fuel cell.

V.B Cost Optimization Results

Capital Cost is higher when we are using Hybrid system with PV. But by using PV we have replacement or Salvage Cost. Operating Cost is higher when we are using standalone diesel-battery system. Replacement Cost for Diesel generator system is way higher than PV-Diesel System. Fuel Cost is higher when we use standalone generator system.

V.C Battery Performance Results

SOC for battery in proposed hybrid system is higher and better as shown in figure 11. Useable Nominal Capacity is also higher in case of PV system. We can vary the use of battery according to weather details and data in case of Hybrid system. Annual throughput/output is higher in case of hybrid system. Autonomy of Battery is higher in Hybrid system. Life time through put is also higher in this system. Storage depletion is also lower in proposed system.

V.D GHG Emission Results:

Energy generation from renewable energy sources reduces the emission of CO_2, SO_2 and NO_x to the atmosphere.

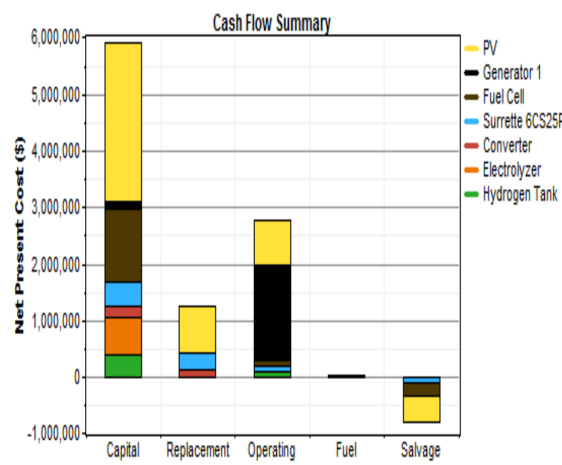

Figure 10: The cost summary of this study by component. All the currency values were considered in terms of BDT instead of $ (USD).

Table 10: Amount of Emission For PV-Fuel Cell-Battery System

Pollutant	Emissions(kg/yr)
CO_2	3869
CO	9.96
Unburnt Hydrocarbon	1.1
Particulate matter	0.751
SO_2	7.77
NO_x	88.9

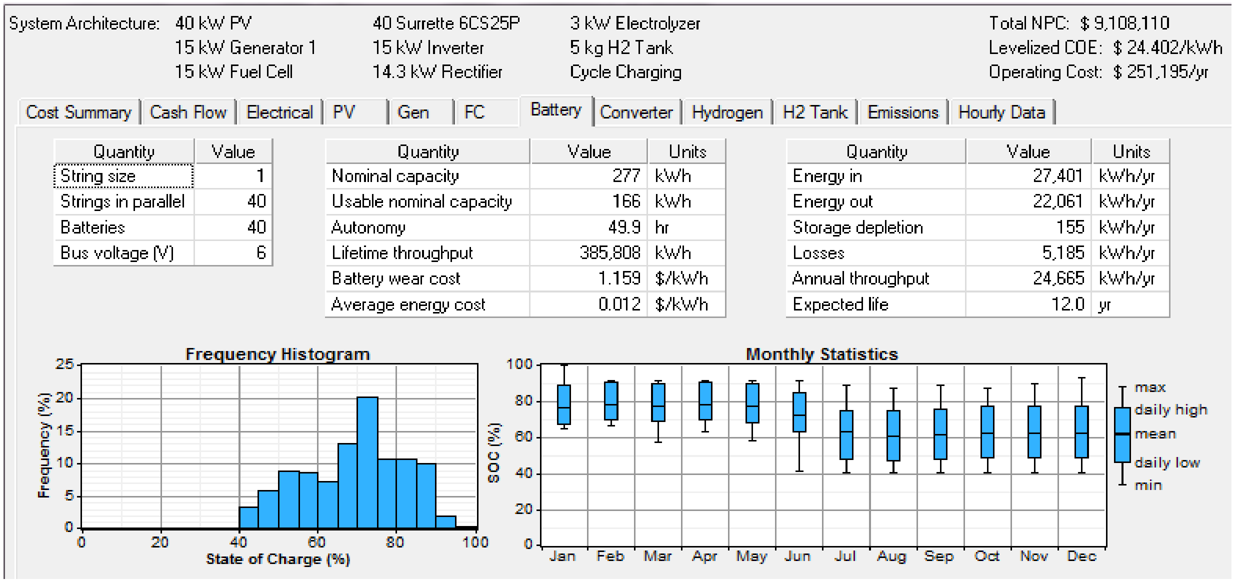

Figure. 11: Battery Charge State for Proposed System

V.E Comparison with other proposed energy systems

There was lots of hybrid system whose feasibility was analyzed by different researcher. A PV-wind-diesel (Ruhul et. al 2014) and PV-diesel (C.A. Salman *et al.,* 2013) was taken for comparison. I am mentioning a comparison in term of some parameter with some hybrid system with the proposed system in the following table.

Table 11: Hybrid Systems Comparison

Parameter	PV-Wind-Diesel	PV-Diesel	Proposed Hybrid System
Initial Cost	2,979,330	3,021,174	**5,896,995**
Operating Cost (BDT/yr)	542,152	1,328,730	**251,195**
Total NPC	10,620,388	18,057,156	**9,108,110**
COE (BDT/KWh)	26.539	55.58	**24.402**
Renewable Fraction (%)	31	41	**94**
Diesel Used (L/yr)	7788	8605	**1470**

VI. Conclusion

In this work, the simulation of a hydrogen based PV-diesel-battery hybrid energy system has been done for St. Martin Island. A system with 40 kW PV array along with a 15 kW diesel generator, 15 fuel cell and 40 numbers of batteries (nominal capacity 1156 Ah, nominal voltage 6V 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. Similarly wind cut in speed of coastal area of Bangladesh is not sufficient for power generation. Experimental result shows that the COE of the optimized system is 0.317 $ /kWh (24.402 BDT/kWh) with 94% renewable fraction which is excellent contribution on our environment. Net present cost (NPC) and operating cost for the optimized system are 116.770$ (9,108,110 BDT) and 3220 $ (251,195 BDT) respectively. This hybrid energy system reduces the emission of CO2 significantly which reduces global warming which is a matter of headache all over the world. For this reason hydrogen based hybrid system will be the most important topic for further research. It is possible to perform the feasibility study of grid-connected hydrogen based hybrid system for rural areas.

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