

Proposition of a PV/tidal powered micro-hydro and diesel hybrid system: A southern Bangladesh focus



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ABSTRACT

Bangladesh being a developing country is struggling for the self-sufficiency of electric power for a very long time. In this run renewable energy can play an important role for electricity generation. Bangladesh abuts by Bay of Bengal, as a result the southern areas face around 2~5 m of tidal head/height rise and fall and as it is in the tropical region it gets an average daylight of 7~8 h per day. Thus the hydro (tidal) energy and solar energy can be the key points to meet the scarcity of power. This paper discusses a model of possible small hybrid power generation system consisting of a PV generation unit with storage and a micro-hydro generation unit and a diesel generator which can mitigate the rising energy demand at the southern areas of Bangladesh. In this paper the economic viability is discussed along with the technical aspects to set up such system via HOMER analysis. Moreover the system cost was analyzed together with a comparison of other system costs of similar capacity.

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1. Introduction

Electricity crisis is one of the core obstacles in Bangladesh. To maintain the industrial and technological growth the need of electricity is an inevitable fact. That is why focus should be given on how the generation of electricity and all the year round continuous supply can be given. Along with the setting up of the new power plants and increasing capacity of the existing plants based of fossil fuels, the Bangladesh government is searching for alternative ways to manage electricity demand as the existing generation plants are unable to meet the demand. In this pursuit hybrid power plants based on renewable energy resources like solar, wind and hydro energy can be of great assistance. The main advantage of this type of plant is the exemption of fuel cost. There is absolutely no fuel cost and if it can be designed appropriately, the maintenance cost is very small compared to the standalone fossil fuel systems. Only the installation cost is countable which is little bit higher than the other systems. The idea of a hybrid power plant is introduced here because it can meet greater load with more efficiency than single resource plants. Moreover the installation cost ratio is lower than single resource plants. The hybrid system consists of a PV system with storage, a micro-hydro power generation system and diesel generation system. The micro-hydro generator uses the water flow of high tide and low tide in the river connected canals for power generation. Feasibility of using micro-hydro power is already been discussed in many literatures [1,2]. For the rural areas, where the electricity is needed mostly for lighting, this type of small hybrid power plant is ideal. Currently only 10% of the rural areas has electricity connection and some parts of Bangladesh may not get the access of electricity connection from the national grid within the next 30 years [3,4]. USAID [5] studied the impact of electrification on the rural society of Bangladesh recently. The results show that it has several positive impacts on the current situation. For example, it increases reading hours up to 93.7% as well as reading habits up to 81%. Adult education probability increases due to the availability of light at night. Economic development opportunity increases as women's working possibility on income generating items increases at night. The study report shows that 78.2% has increased in working hours and 62% has increased in rural household income. As fuel cost reduces, the overall daily expenses are also reduced. The amount of reduction is reported 93.7% in the fuel cost. Other reduction of expenses includes medical treatment related costs from using kerosene lamps. Standard of living will be improved up to 92% as well as 94.7% improvement in security. Here we are to discuss the potentiality and design of a solar and tidal energy based micro-hydro combined with Diesel generator power station. In this paper a design of the system is proposed and also the financial prospects are analyzed by the HOMER software.

2. Energy resources of Bangladesh

The study conducted by Chowdhury and Reza [6] reveals that Bangladesh is a land of renewable energy resources. The main two renewable resources with diesel which can contribute the most in

the electricity generation market are discussed in the following subsections.

2.1. Solar resources

Bangladesh is situated between 20°30' north and 26°38' north latitude. In this range solar energy is comparatively higher, where the highest is in 15° and 35° latitude north and south. In Bangladesh the solar radiation is also 50–100% higher than the European countries. Here the radiation availability varies between 4 and 6.5 kWh per square meter on a daily basis [7], and the daily duration is around 7–8 h on the seasonal basis [8]. As a result, the average per year radiation availability ranges from 1460 kWh/m² to 2372 kWh/m². The energy demand can easily be met if solar energy can be used properly [6].

2.2. Micro-hydro resources

Bangladesh is a land of rivers. The major rivers of the country originated from The Himalayas which is at the north of Bangladesh and on the south stands the Bay of Bengal where all rivers meet the sea. Hence, the water flows mainly from the north to south direction. A recent study of Sustainable Rural Energy on the prospect of micro-hydro power plants in southern Bangladesh shows that one region consisting eight potential sites can contribute up to 135 kW [9] to the national power grid. These statistics exclude tidal power. Researchers pointed out several locations in southern Bangladesh where tidal energy is usable [10]. In fact, a system consisting 75 kW micro-hydro turbine using tidal energy is already proposed in Sandwip, Bangladesh which can produce 1380 kWh per day [11]. The rivers and river connected canals of the southern parts of Bangladesh face high tide with the height of around 3.5 m and low tide of 0.5 m [12]. Therefore the tidal energy can be used for power generation. A yearly average chart of the tide height is given in Fig. 1 below.

Based on the figure, if micro-hydro plants can be set up on the canals, sufficient power can be generated easily from the tidal water resource.

2.3. Diesel availability

Diesel is one of the key resources for electricity generation. It is used to run dispatchable and back-up oriented generators in this study. From this point of view diesel price contributes an important role in modeling any power system. Depending on the diesel price the optimum configuration of a system can be changed. According to the Bangladesh Petroleum Corporation [13] the diesel price is 68 BDT/liter equivalent to 0.8 USD. As there is no subsidy in diesel price in Bangladesh, the price may vary time to time based on the world oil market. The total NPC as well as COE will change based on the diesel price. This makes forecasting vulnerable and this source troublesome in the long run.

3. Case study development

3.1. Location

As the analysis is based on the southern part of Bangladesh, the location chosen is a village of Barisal division. The chosen village named Dhankhali comes under the Kalapara sub-district in Patuakhali district and is situated at 22.007°N and 90.29°E. There is electricity supply from the Rural Electrification Board in the main Kalapara sub-district, but the supply is yet to cover this area. There are around 884 people (of which 443 are male and 441 are female) living in this village and the average size of each household is 4.1 people but the size of the household follows a bell-shaped curve with a minimum of 2 persons and a maximum of 8+ persons, as per 2011 census [14]. This refers that, there are around 200 families that need to be brought under the electricity coverage. The men of this village are mostly farmers and fishermen and the women look after the household works and are engaged with some handicraft related product making. Most of the people live in the kutchha houses (85.2%) owned by them and the rest of them live in semi pucca (3.3%), pucca (1.6%) and jupri (9.9%) houses. Most of the people are under the poverty curve. Being non electrified the village people depend on kerosene and candles for lighting and there is no way of having fans or electronic recreation media such as radio and television. This village is on the bank of Dhankhali River which runs into Rabnabad channel to meet the Bay of Bengal. There are two major canals in the village. These canals support the villager with water for irrigation and also protect the village from overflowing water during the monsoon and high tide time. As the river is very near to the sea, the tide height difference is significant and during the high tide time, the river connected canals face water height of 4–5 m and low tide height is around 0.5–1 m. There are several sluice gates in the canal for water reservation purposes which are opened and closed on tide time basis. This opportunity can be used to produce electricity via the micro-hydro turbines. There is sufficient water level height and also water flow which can rotate small turbines and produce electricity.

3.2. Proposed hybrid energy system

The implementation of the hybrid system is more efficient and easy to maintain. It is also cost effective than the different standalone installations. Different configuration of the hybrid energy system has already been proposed based on different areas and

the resources available in that area [15–20]. Without solar, wind and water energy, no other renewable energy is available to naturally produce sustainable energy [21]. Therefore a model of hybrid system is proposed which combines a PV based solar power system and tidal water based micro-hydro-electric power system and a diesel generator. Generally, micro-hydro power includes generating from 5 up to 300 kW of electricity through the hydroelectric power depending on the availability of water stream flow [22]. As the southern part of Bangladesh has enough energy resources for this type of hybrid electricity generation system, Dhankhali, a place near Barisal was selected to set up such system [14]. The system design considers the load profile for hundred houses for 24 h. This number is considered based on the available hydro resources to support the load, although there are 200 households in the village. The nominal load profile for a single home in the remote area is given in Table 1 below:

For hundred houses the total energy consumed per day will be $2.24 \times 100 = 224$ kWh/day. This data is considered in the HOMER software as hourly load demand to get the daily and monthly load profile for the whole year. The load profiles are as follows:

As the main use of electricity in the rural areas is lighting, it can be determined from Fig. 2 that the peak duration will be from 6.00 pm to 11.00 pm. In this period any of the three sources can operate depending on the micro-hydro resources. If the available micro-hydro resource can meet the load demand, it will operate singly; if not the power needs to be top up by the diesel generator and PV-battery system.

The micro-hydro resources are variables according to the seasons and time. During summer the water level is high and in winter the water level is low. The daily tide times also vary and do not occur at a fixed time. Fig. 4 shows the time difference between high and low tide and the day to day tide time shift for the month of January 2014. The tide time shifts all the year round in almost the same way keeping the time difference from 5 h to 7 h. Thus it can be inferred that the micro-hydro will operate for around 6 h continuously. Then after 5–7 h interval it will work again. However, the operating time will shift from day to day. In the time interval PV system with battery backup and the diesel generator will supply the whole load. As the PV source is not generating power at night, the diesel generator and the battery system will meet the load demand if the micro-hydro resource is not available.

Same as generation, the load profile also varies according to seasons. During the summer season the load is higher than the winter season. This seasonal variation is also considered in HOMER with the daily load profile. The load calculation is done based on rural electrification, and the load demand is mostly for lighting and fan. In the morning (6–11 am) the sunlight is enough and at that time the temperature is low enough so that there is no need of light and fan. Moreover, in the rural area, the villagers cannot afford other home appliances such as refrigerators or washing machine, so this type of loads are not considered. Therefore, no load is considered at 6–11 am. The schematic diagram of the system is given in Fig. 5.

Mathematical modeling components of the energy system are necessary to obtain the capacity calculation. The proposed system consists of diesel generator, PV system with battery and micro-hydro generating subsystems. The theoretical expressions can be found in the work of Lal et al. [23].

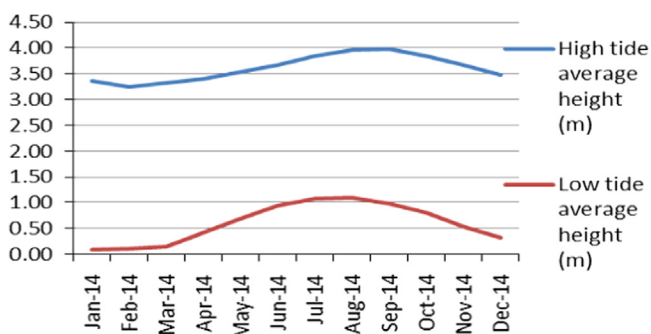


Fig. 1. Average high tide and low height forecast over a year for Chittagong [12].

Table 1
Load details for a single house.

Units	Quantity	Power consumed (W)	Uses (h/day)	Energy consumed (Wh/day)	Total energy for single house (kWh/day)
Energy saving bulbs	6	25	6	$25 \times 6 \times 6 = 900$	2.24
Fan	2	35	12	$35 \times 2 \times 12 = 840$	
TV set	1	100	5	$100 \times 1 \times 5 = 500$	

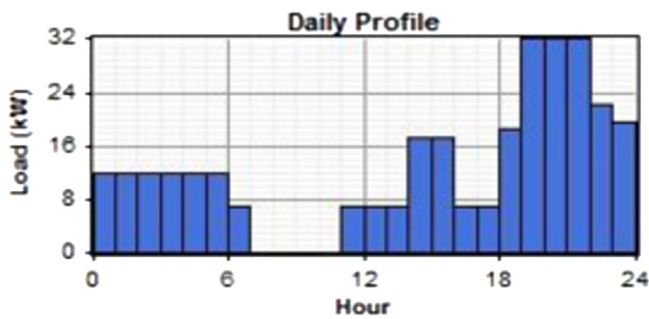


Fig. 2. Daily load profile.

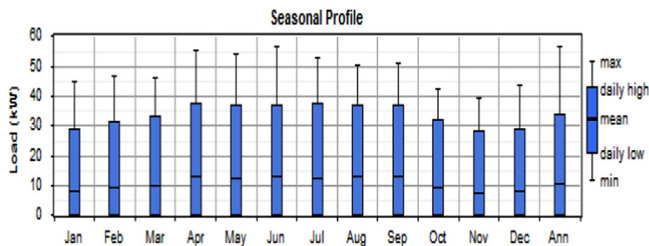


Fig. 3. Monthly load profile.

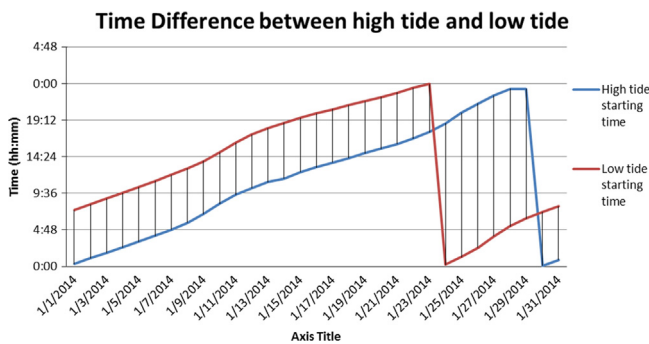


Fig. 4. Time difference between high tide and low tide [12].

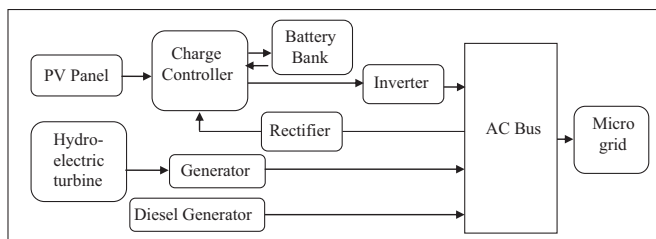


Fig. 5. Schematic diagram of solar PV and micro-hydro power plant.

4. HOMER simulation

HOMER is the simulation software developed by the National Renewable Energy Laboratory (NREL), United States. Several other software like Hybrid2, Simulink, HOGA (Hybrid Optimization using Genetic Algorithm) are available which can do the hybrid system modeling [24,25]. Apart from HOMER, other software models mainly the technical details and solved the constraints rather than focusing economic aspects. HOMER is chosen due to its capability of doing both financial and technical analysis, availability and widely acceptability for microgrid modeling, although it takes time to grasp its complete capabilities. Moreover, it can model the life cycle cost, installation and maintenance cost, operating cost and can be compared with other design options based on technical and economic aspects. The input data of HOMER is the size and price of

each component, resource data such as solar radiation, water height and flow rate and economic constraints such as fuel price, annual interest rate. Based on these input values it provides the component sizing, the costs associated with it, energy generation and consumption details and some other economic aspects of the system. The hybrid system was designed and simulated in HOMER to get the optimum data to determine the ratings of PV, battery, micro-hydro generator and converters for the considered load profile. In this simulation the influence was given on the minimum COE (cost of energy), however other parameters such as capital cost, total NPC (Net Present Cost), installation cost, replacement cost, operation and maintenance (O&M) cost etc. were also considered to get the optimum system configuration. The component price considered in the simulation was based on the current market price and it was taken from the manufacturers' websites.

4.1. System design specification

For the simulation purposes the system component specifications were given in the HOMER software and the single line diagram of the system generated by HOMER is shown in Fig. 6. Here, the primary load was of AC type and the power generating units were both AC and DC. Therefore two buses were created and they were combined by power converters. The DC power sources were battery and PV panel and the AC power sources were micro-hydro turbine and two diesel generators of different ratings.

The solar irradiance data was taken from the internet by providing the latitude and longitude data of the place in the homer system. It can also be obtained from Bangladesh Meteorological Department website [9]. The data of Fig. 7 shows that the solar radiation was lower from July to September due to the rainy season and during this time the clearness index was also low. However, in the other months both the radiation value and clearness index were high enough to produce good amount of electricity.

The tidal forecast data obtained from the tide table was considered in the HOMER system for the hydro resources. The tidal forecast data shown in the Fig. 8 was based on the southern part of Bangladesh for the year 2014. It shows that the stream flow varies between 290 L/s and 470 L/s in a year. The average stream flow is 372 L/s. This stream flow is of the river of southern Bangladesh.

4.1.1. AC load: primary load

The load profile obtained from the calculation for supporting hundred houses in the southern Bangladesh was considered into the HOMER software. The hourly and monthly basis load profiles generated by HOMER are provided in Figs. 2 and 3. Fig. 2 is for the load profile based on per hour and it is clear that the load demand was high from 6.00 pm to 11.00 pm. That is because the main load demand for rural areas is lighting. Other load demands such as fan,

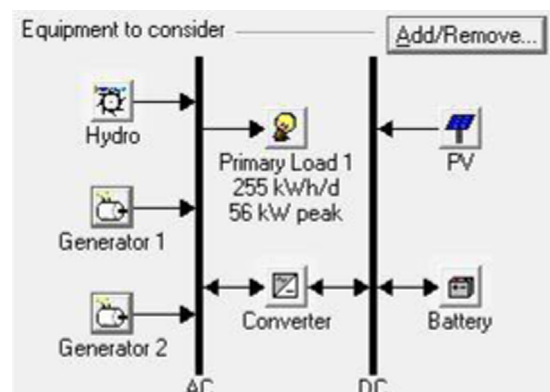


Fig. 6. Single line diagram of hybrid energy system.

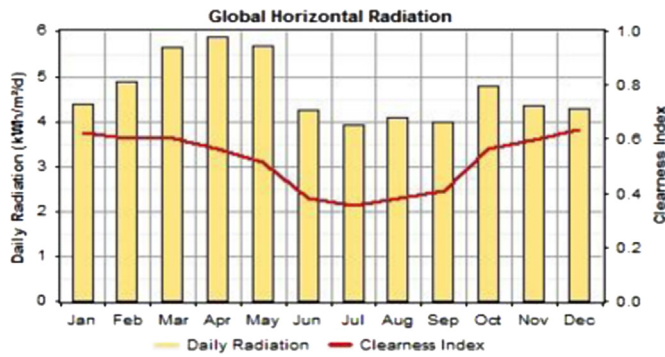


Fig. 7. Solar radiation data.

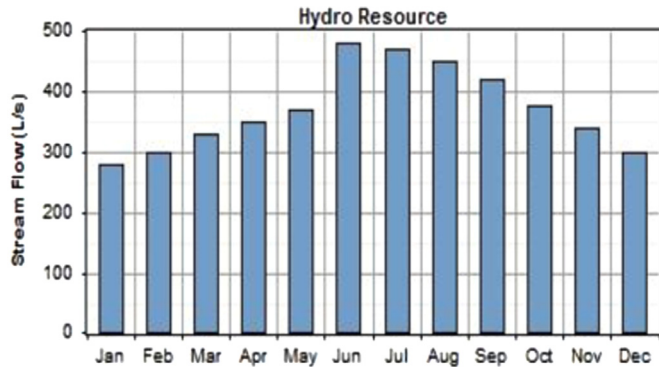


Fig. 8. Hydro resource inputs.

TV are lower than lighting. Fig. 3 shows the load demand for the whole year on monthly basis. It proves that there were changes in the load based on the seasonal changes, although it was not high enough to affect the controlling system and the source capacity. In the summer season the load as well as supply was higher than the rainy and winter season. Here in HOMER the data was considered to be more practical rather than being analytic. For this reason 15% day to day and 20% hour to hour noise were added in the load profile. The scaled annual average load was 255 kWh/d and at the load factor 0.189 the scaled peak load was 56.2 kW which we obtained from the HOMER load profile.

4.1.2. PV panel

In HOMER a range of PV capacity was considered for obtaining the optimum result. The power generated from the PV system was supposed to serve the load as well as charge the batteries at low demand times. The lifetime of the PV panel is considered as 18 years where the normal recommendation of a lifetime is 20 years. It was done to consider the worse cases, because the HOMER simulation does not consider any accidents that can happen to the PV panels. The price of PV panel was determined according to the market price of 265 W Mitsubishi PV-MLE265HD mono-crystalline solar panel [26]. The installation cost and replacement costs were taken as similar (\$1050/kW). Although the maintenance cost was near to zero, a lump sum amount was taken into consideration which was 20 \$/year. In the preparation, the tracking system used was horizontal axis, monthly adjustment type. It was to ensure the maximum power was extracted from the PV panels. For the implementation purposes the MPPT can be excluded and a tilted angle surface can be used to avoid extra expenses. A ground reflectance of 20% was included in the study. The lifetime of the PV panel was considered 18 years and lastly the derating factor was considered 80%.

4.1.3. Micro-hydro turbine

There were several issues to consider while choosing the right micro-hydro generator like the types of turbine, the capacity of turbine, the water height, and the water flow rate and so on. The Kaplan type hydro turbine is suitable for low head of water. Based on the available resources such as available head and water flow rate, the nominal power of the water turbine was determined as 8.21 kW. Based on these facts, the turbine chosen for the system was Ampair DRK HT turbine [27]. This turbine is available at the local market and provides installation and cost free maintenance supports initially. The initial cost for the micro-hydro turbine was \$ 40,181 and the replacement cost was \$ 20,000. The O&M cost were taken as 100 \$/year and the lifetime of micro-hydro turbine was considered 20 years.

4.1.4. Battery: Surrette 6CS25P

The storage used by the PV system was a battery bank. The DC bus considered here was 24 V, so the battery connection was assumed as 4 units per string of each unit of 6 V. The number of battery considered for simulation purposes were 16–52 on a 4 numbers interval. The selected number of batteries was 28. The battery model used in the system was Surrette 6CS25P [28]. The cost of a single unit was \$1170, a similar figure considered as the replacement cost and the O&M cost was negligible, therefore it was taken as 2.5 \$/year. The batteries were modeled as perfect storage devices, where losses only happens in charging and discharging periods and there was no other effect considered such as temperature or shunt current loss. The roundtrip efficiency was taken as 80% and the capacity of each battery was 1156 Ah. The lifetime throughput is 9655 kWh, thus the battery lifetime was taken as 3 year minimum. However, it can vary based on the usage in the system. The minimum state of charge (SOC) was at 40% which was defined by HOMER.

4.1.5. Converter

The converters or various capacities were used to get the optimum one. In this system three types of converters were needed. They were: DC–DC converter with battery charge controller, rectifier and inverter. However HOMER considers them as an integrated converter. The range of input was given at 10–30 kW and the selected specification of the inverter as well as rectifier was of 12 kW. The initial cost for the converter was \$13,152 and the replacement cost was considered as \$11,445 [29,30]. There was no O&M cost for the converters in the study. The efficiency of the conversion from AC to DC and vice versa was considered as 90%, and the converter was supposed to have the same efficiency relative to the inverter and the ability to operate with the AC generator. The lifetime of the converter was considered as 10 years.

4.1.6. Diesel generator

In the system, two types of diesel generator were considered. The small sized 5 kW generator was for meeting the low power demands and the big sized 10 kW generator was for high power demand. This classification may increase the initial cost but will be effective in terms of fuel efficiency and cost of energy. This method was followed by observing the real scenario of the oil based power plants in Bangladesh, where power supply was done by load categorizing. The Capital and replacement price are given in Table 2. It is worth mentioning that, the lifetime of each generator was estimated to be around 15,000 h of operation [31,32].

Although the single generator of 15 kW was available for the load supply, two generators of 5 kW and 10 kW were used because the mission of this study was to optimize the diesel generators efficiency by operating it at near to the full load for different load conditions. The operating method was such that, when the load was below 5 kW, only

the 5 kW diesel generator will operate and when the load was between 5–10 kW, the 10 kW generator will be functional. And when the load was greater than 10 kW both of the generators will operate. This method of operation reduces the overall fuel consumption. Homer permits to input the fuel curve data received from the data-sheet and the resultant curves for each generator are shown in Fig. 9 (a)–(d). The fuel curve and efficiency curve help homer to define the fuel consumption and generating efficiency of diesel generator.

4.1.7. Financial assumptions

In the previous sub-sections the cost estimation was shown in a straight forward and simple way where only initial capital, replacement cost and (O&M) cost were taken into account. Practically, the costs for each equipment would differ from the estimations given and would be in more detailed and complex manner.

According to IRENA (International Renewable Energy Agency) report [33], there are numerous methods to estimate the cost of power generation and each method has its own insights. Some other cost parameters which can be included in the analysis are: financing cost tariffs and rents, hardware assembly cost, control system deployment cost, total installation and management cost and so on. The cost analysis part was simplified because of the transparency and comparison purposes. It provides the opportunity to scrutinize the data assumptions and improve the transparency and confidence to analyze and compare the costs of each technology to identify the key points of differences. Moreover, for the technological comparison, researchers prefer the average cost

Table 2
Cost data of diesel generator [31,32].

Size (kW)	Capital (\$)	Replacement (\$)	Operation and maintenance (\$/h)
5	500	500	0.25
10	3600	3600	0.25

estimation which can be forecasted from the simplified economics. In this study there is no system fixed capital cost as well as no system fixed O&M cost undertaken. It is done to bring the analysis at the same platform with other systems studies [34]. Lastly, the annual rate of interest was considered as 6% which was taken from the local financial market analysis. The lifetime of the system was considered 25 years.

4.2. System analysis

The simulation result is shown in Table 3. The optimum solution is given with some other configurations to prove that the selected one is the best system. The detailed report is discussed in the following sub-sections.

4.2.1. Sensitivity report

HOMER produces a lossless model because the assumption made in the simulation was that the power source was close to the load. As a result there was no transmission or distribution loss. Again, the load modeled here was residential load only and a shortage capacity of 10% per annum was considered. The dispatch strategy of the system was considered as CC (cycle charging) mechanism. The mechanism demonstrates that when the battery SOC (state of charge) was lower than the minimum point (40%), it would force the generator to start and charge the batteries and when the maximum (SOC) point was reached (80%), the generator would be turned off if there was no load demand for the generators. Now for matching with the local environment and the local financial market, the following sensitivities were considered. Capital cost multiplier: 1, PV replacement cost multiplier: 1, Hydro Capital cost: \$ 40,141, Annual Interest Rate 6%.

Table 4 shows the annual production of each sub units and load consumption. From the table it can be seen that the total generation and consumption are 109,779 kWh/yr and 91,141 kWh/yr respectively and the major contributor of the power generation is

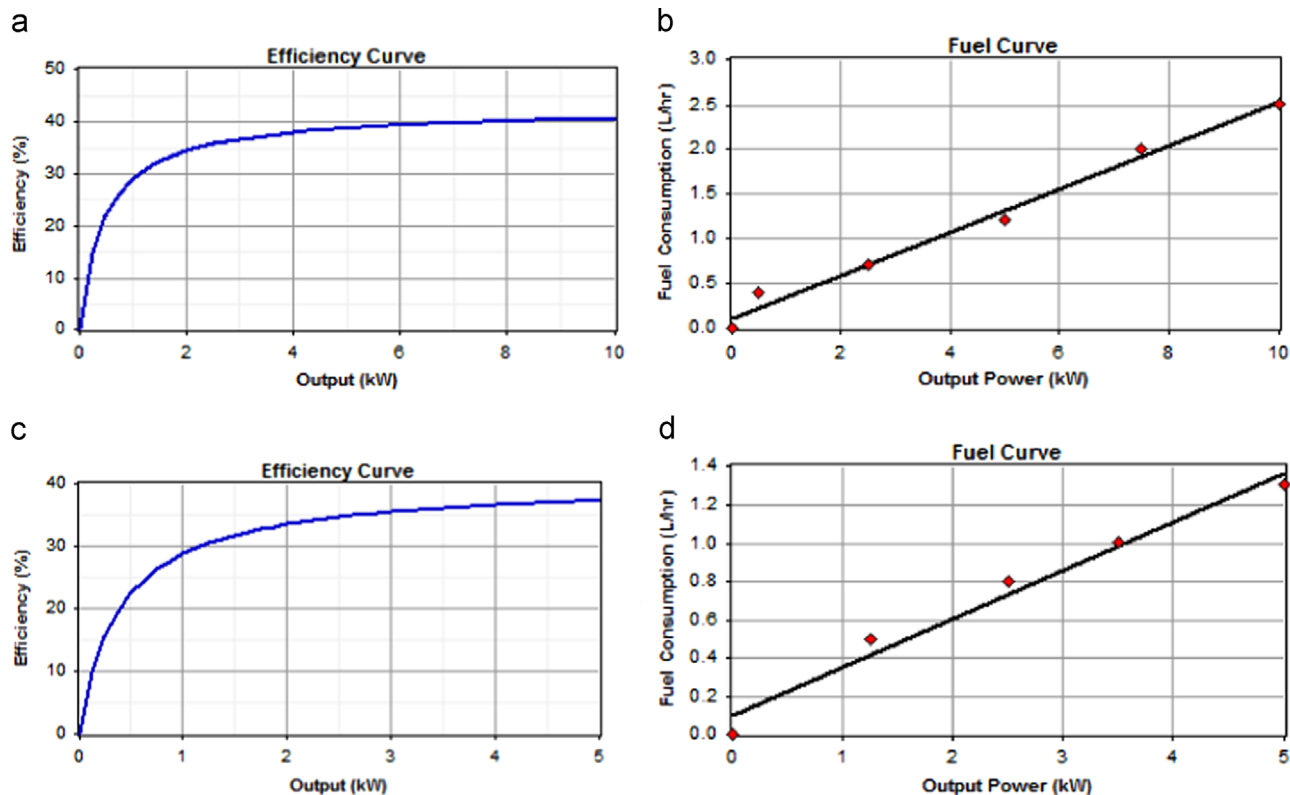


Fig. 9. (a) 10 kW Diesel generator efficiency curve, (b) 10 kW diesel generator fuel curve, (c) 5 kW diesel generator efficiency curve, (d) 5 kW diesel generator fuel curve.

Table 3
Simulation results of the system.

PV (kW)	Hydro (kW)	Generator 1 (kW)	Generator 2 (kW)	Battery	Converter (kW)	Initial capital (\$)	Operating cost (\$/yr)	Total NPC (\$)	COE (\$/kWh)	Renewable fraction	Capacity shortage	Diesel (L)	Generator 1 (h)	Generator 2 (h)
7	8.21	10		24	10	90,171	11,668	239,332	0.211	0.76	0.08	9269	4245	
5	8.21	10	5	20	10	83,891	12,251	240,506	0.206	0.64	0.04	10,199	2496	3407
7	8.21		10	28	10	92,251	12,380	250,510	0.221	0.68	0.08	9657		3842
28		10	5	28	12	79,412	21,160	349,906	0.315	0.35	0.10	18,300	4726	5814
22		20		24	10	69,340	22,967	362,940	0.315	0.27	0.06	20,226	4835	
20			20	28	10	66,720	25,195	388,801	0.338	0.25	0.06	21,989		4626

Table 4

Annual electricity production and consumption.

Production			Consumption	
Component	kWh/yr	%	Component	kWh/yr
PV array	6773	6	AC primary load	91,141
Hydro turbine	63,873	58		
Generator 1	24,951	23		
Generator 2	14,183	13		
Total	109,779	100		

Table 5

Sensitivity report.

Quantity	kWh/yr	%
Excess electricity	12,255	11.2
Unmet electric load	1934	2.1
Capacity shortage	3607	3.9
Renewable fraction		64.4

the micro-hydro unit. It generates 63,873 kWh/yr and it is 58% of total electricity generation. The second highest contribution comes from the diesel generators. The 10 kW and 5 kW diesel generators produced 24,951 kWh/yr and 14,183 kWh/yr respectively. They are 23% and 13% of the total yearly generation. The least amount of power is delivered by the PV system and it was 6773 kWh/yr, which was only 6% of total generation.

The statistics of the effectiveness of the system is given in Table 5, where the amount of excess production, unmet electric load amount and shortage of load demand are given. Here HOMER used the term unmet to indicate the unfulfilled load of the system. This table is a proof of how effectively the system can handle the loads with the minimum amount of electricity wastage. It shows that the excess electricity was only 11.2% of the total generation, which means the system produced this extra amount after meeting the load demand and it was the wastage of the system. The system would be an ideal one if this amount was zero. However it was not possible due to every practical system should have some extra electricity generated for reserves. Thus, the best system based on this sensitivity parameter was considered for. Again, the unfulfilled load for the system was only 2.1%. This means the system was capable of handling most of its electrical loads and the capacity shortage was also 3.9%, and this parameter indicates that only 3.9% of the generation capacity was the shortage of electricity. If this amount of the system could be produced according to the timing of load demand, the system would be of no shortage and become an ideal one for the project. The renewable fraction of the system was 64.4% which indicates the use of renewable energy in the system and the rest part was diesel generator. This parameter shows that the proposed system operated mostly on renewable energy and also reduced the use of fossil fuel.

The cost calculation for the proposed system is given in Table 6 below. From the table it can be referred that, if we consider the total cost, the generators have the biggest cost percentage in the system and it is due to the high fuel cost and maintenance cost. Then comes the micro-hydro generator. The reason behind the high cost of micro-hydro generator is its high initial cost. There is no fuel cost and the maintenance cost of it is very low. The high price of the battery makes bigger initial cost for battery section, although there is very low maintenance cost. Comparatively PV panel and converter cost are lower than the other part. The reason behind it is the size of PV panel as well as converter are not considered bigger due to the high price of PV and the inconvenience of setting up PV panels. PV panel set up requires bigger area and unused lands which are hard to get. Moreover bigger area

Table 6
Cost detail.

Component	Capital (\$)	Replacement (\$)	O&M (\$)	Fuel (\$)	Salvage (\$)	Total (\$)
PV	5250	1839	64	0	– 748	6406
Hydro	40,181	6236	1278	0	– 3495	44,200
Generator 1	3600	6470	7977	64,129	– 705	81,471
Generator 2	500	1236	10,888	40,172	– 37	52,758
Battery	23,400	17,408	639	0	– 4998	36,450
Converter	10,960	9537	0	0	– 1277	19,221
System	83,891	42,727	20,846	104,301	– 11,259	240,506

Table 7
System component specification.

Component	Size
PV	5 kW
Hydro	8.21 kW
Surrette 6CS25P Battery	20 (1156 Ah each)
Generator 1	10 kW
Generator 2	5 kW
Inverter	10 kW
Rectifier	10 kW

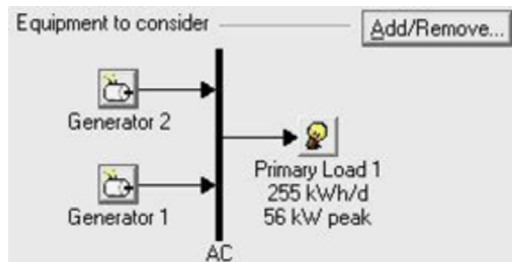


Fig. 10. Stand-alone diesel system scheme.

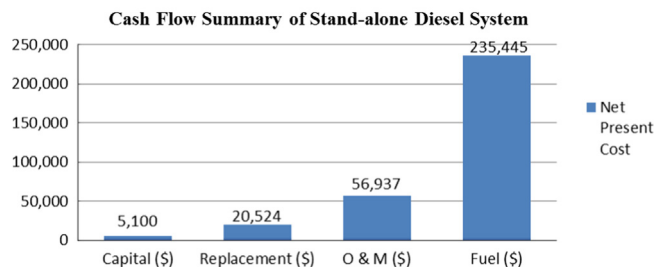


Fig. 11. Cash flow summary of standalone diesel system.

will increase the rental cost which was not included in the analysis. The initial capital for the system equipment was \$83,891 and the total net present cost was \$ 240,506.

4.2.2. System architecture

The size specification of each component is given in Table 7.

4.2.3. Cost summary

Total net present cost:	\$ 240,506
Levelized cost of energy:	\$ 0.206/kWh
Operating cost:	\$ 12,251/year

4.2.4. Annual outcome

From the system the annual electricity production is 109,779 kWh/year and the levelized cost of energy is 0.206 \$/kWh.

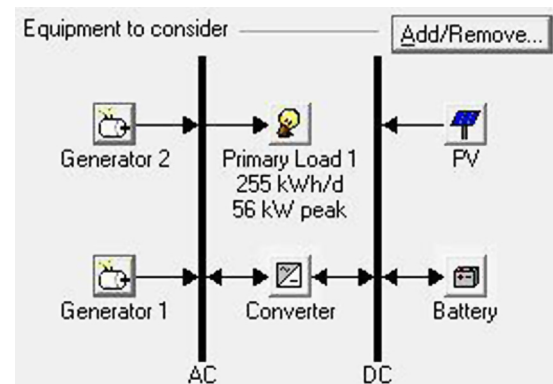


Fig. 12. PV/diesel/battery hybrid system scheme.

Cash Flow Summary of PV/Diesel/Battery System

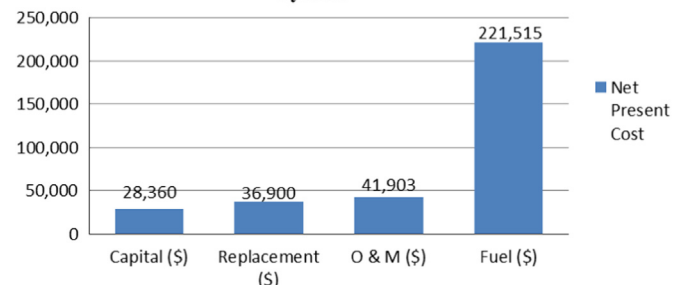


Fig. 13. Cash flow summary of PV/diesel/battery hybrid system.

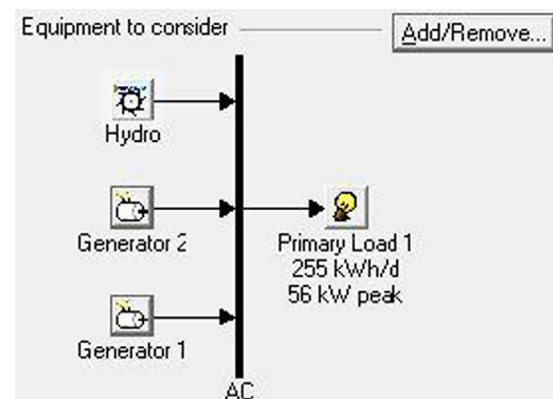


Fig. 14. Micro-hydro/diesel hybrid system diagram.

Therefore, the annual outcome from the system is $109,779 \times 0.206 = \$ 22,614.47$. The annual operating cost is \$ 12,251. Hence, the Net annual outcome is $(22,614.47 - 12,251) = \$10,363.47/\text{year}$.

5. Comparative analysis of energy systems

There are some other hybrid systems which can be compared with the proposed PV/micro-hydro/diesel hybrid system. In order to check the validity of the system a comparative study has been done. A simulation for the same load profile has been done for one single source and two other hybrid systems. The single source system is a conventional approach which is very common in power generation. The capacity of the diesel generators is considered different for different load conditions. The second system is a hybrid system consisting PV with battery and diesel generators. This kind of hybrid system was previously analyzed by Lau et al. [35], Tijani and Tan [16]. The next system simulated in this study was a hybrid system including micro-hydro and diesel generators. This type of system was previously suggested by Kababjie and Hamdon [36]. Finally the proposed system performance was also simulated. The referred literature are based on different location, load profile and simulation settings. In this study only the system configuration ideas were considered from the publications. All the three different configurations simulated kept the load profile and other simulation settings fixed and the results were compared with the proposed system. The lifetime of

the systems was considered 25 years. The simulation details are elaborated in the following subsections.

5.1. Diesel generator

The scheme illustrated in Fig. 10 is a conventional way of supplying the load with only diesel generators. The simulation results show that, this system has the lowest initial cost (\$5100). However, the economy depends on the diesel price. With the increase of fuel price the cost of energy as well as the NPC increases proportionately. Fig. 11 illustrates the cost of this system chronologically. One of the main constraints of this configuration is that it has the largest emission of pollutants which is given in Table 9. The total emission recorded from the system was 62,260.9 kg/year. The excess electricity generated by the system is 161 kWh/year, which is only 0.2% of the total generation capability. That means the system is very efficient in load handling. Again the capacity shortage is 10.2% of generation capability. This system is not recommended because it has the greatest contribution to global warming and also it has fuel transportation constraint.

5.2. PV/diesel/battery hybrid system

Diesel generator has some constraints such as high emission, greater fuel consumption and high maintenance cost. To minimize the constraints PV/diesel/battery hybrid system can be introduced. This configuration is illustrated in Fig. 12. Similar to the only diesel driven configuration the economics of this hybrid system also depends on the fuel cost. Moreover, the plant also emits pollutant gases. Nonetheless, the amount of pollutant is much lower than the only diesel system. The total emission is 58,757.2 kg/year. In Fig. 13 the cash flow of the system for its lifetime (25 years) is shown. The costs can be arranged from highest to lowest, that is fuel cost (\$ 221,515), the operating and maintenance cost (\$ 41,903), capital cost \$ 28,360 and replacement cost \$ 36,900. The excess electricity generated is 6.67% of the total generation capacity. The capacity shortage (6688 kWh/year) is 7.19% of total generation. These sensitivity results prove the wastage of electricity is high as well as the capacity shortage. The capacity shortage can be minimized by selecting larger generators, but it increases the costs and HOMER does not support that

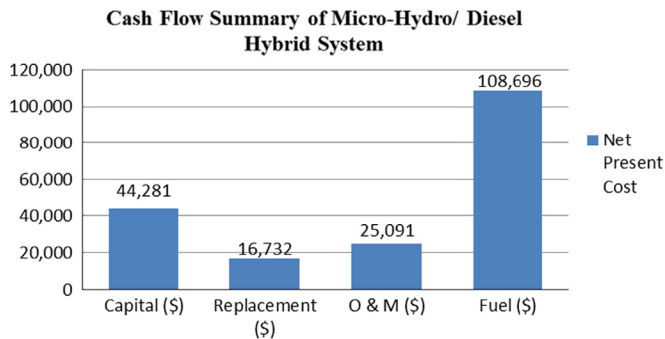


Fig. 15. Cash flow summary of micro-hydro/diesel hybrid system.

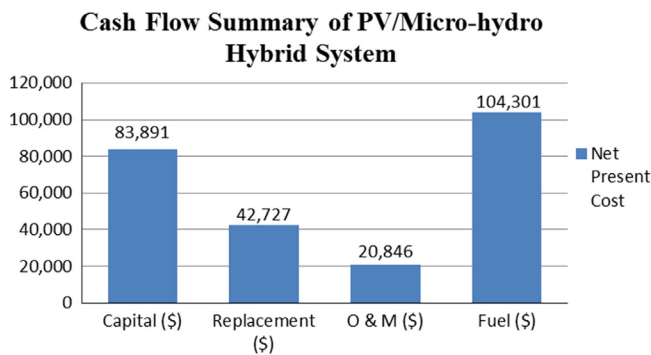


Fig. 16. Cash flow summary of PV/micro-hydro/diesel hybrid system.

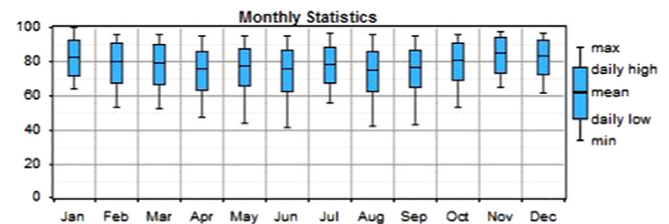


Fig. 18. State of charge of the battery bank.

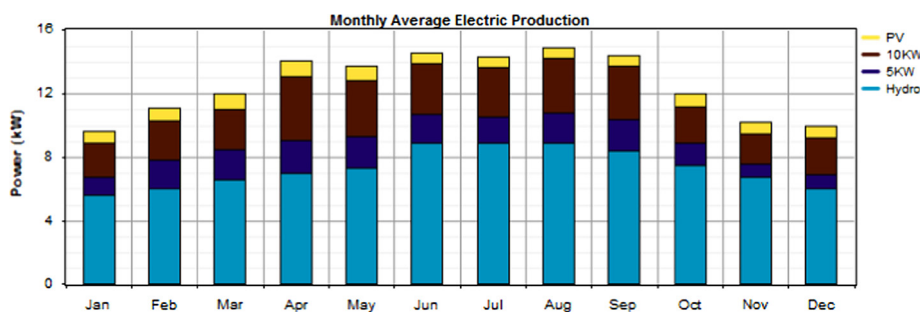


Fig. 17. Monthly average electricity production from PV/micro-hydro hybrid system.

Table 8
Comparison of different systems.

Systems	Diesel generator	PV/diesel/battery hybrid	Micro-hydro/diesel hybrid	Proposed PV/micro-hydro/diesel hybrid
Total NPC (\$)	317,300	326,123	191,084	240,506
Levelized COE (\$/kWh)	0.286	0.287	0.179	0.206
Operating cost (\$/year)	24,422	23,293	11,484	12,251
Capital cost (\$)	5100	28,360	44,281	83,891
Replacement cost (\$)	20,524	36,900	16,732	42,727
O&M cost (\$)	56,937	41,903	25,091	20,846
Fuel cost (\$)	235,445	221,515	178,908	104,301
Production (kWh/yr)	86,808	97,547	100,872	109,779
Consumption (kWh/yr)	86,647	88,822	83,662	91,141
Excess electricity (kWh/yr)	161	6504	17,214	12,255
Unmet load (kWh/yr)	6428	4253	9413	1934
Capacity shortage (kWh/yr)	9518	6688	13,158	3607
Total emission (kg/year)	62,260.9	58,577.2	28,743.16	27,581.54

configuration as the optimized one. The main advantage is it recovers the high use of fuel of only diesel driven system and also reduces the high capital costs of PV-battery system. It has an acceptable net present cost and operating cost. However, as the system is not efficient enough and it is harmful for the environment due to its pollutant emission, it is not suggested for implementation. Bala et al. proposed the viability of such system which produces 23,112 kWh which costs 48,823 Euro equivalent to \$ 60,974 [37].

5.3. Micro-hydro/diesel hybrid system

The one-line diagram in Fig. 14 shows the configuration of micro-hydro/diesel generator hybrid system. The optimum configuration for the load includes 8.21 kW micro-hydro generator and 15 kW diesel generator. The system NPC is \$ 191,084, cost of energy is 0.179 \$/kWh and operating cost is 11,484 \$/year. Fig. 15 illustrates the cash flow summary of the scheme.

The largest cost of the structure is fuel cost (\$ 108,696) because there are two diesel generators in the system. The other large amount of costs are the capital cost (\$44,281) and O&M cost (\$ 101,372). The O&M cost is high due to the moving parts maintenance of the generators. The replacement costs are comparatively small, because the system configuration has reduced the component count significantly. The total production of the power plant is 100,872 kWh/yr and consumption is 83,662 kWh/yr. Therefore, the excess electricity production is around 17.1% of the total capacity. The capacity shortage (13,158 kWh/yr) is 14.1% of the generation capacity. The capacity shortage and excess electricity generation is high for this system. The advantage of the system is it has the lowest cost of energy (COE) and net present cost (NPC). However, the high emission of pollutant gases generated by the system illustrated in Table 9 has an environmental impact. This configuration is the closest competitor of the proposed system. It has better economic prospects but the environmental impact is worse and the renewable energy usage is low.

5.4. The proposed PV/micro-hydro/diesel hybrid system

The configuration illustrated in Fig. 5 is based on PV with storage, diesel and micro-hydroelectric power generation system. The simulation results in Table 3 illustrate several configurations for the PV/micro-hydro/diesel hybrid. Homer shows that the optimized structure has only the large diesel generator to lower the fuel cost. However, that solution has a shortage of electricity of 8%. For maximized uptime here the second combination is suggested. Also it has the lowest cost of energy (COE) of 0.206. The cash flow summary in Fig. 16 shows that fuel cost (\$ 104,301) and capital cost (\$ 83,891) are higher compared to the other costs. The high

Table 9
Pollutants emission of the systems.

Pollutant	Diesel (kg/yr)	PV/diesel/battery hybrid (kg/yr)	Micro-hydro/diesel hybrid system (kg/yr)	PV/micro-hydro/diesel hybrid system (kg/yr)
Carbon dioxide	60,626	57,039	27,989	26,857
Carbon monoxide	150	141	69.1	66.3
Unburned hydrocarbons	16.6	15.6	7.65	7.34
Particulate matter	11.3	10.6	5.21	5
Sulfur dioxide	122	115	56.2	53.9
Nitrogen oxides	1335	1256	616	592

capital cost is due to the large number of batteries for back up and two types of generators being responsible for the high fuel costs. The large number of batteries also causes large replacement cost (\$ 42,727); however the O&M cost is the lowest (\$ 20,846). The excess electricity generated is about 11.2% of the total energy generated and the capacity shortage (3607 kWh/year) is 3.9% of the total capacity. From the aforementioned data, it is clear that the proposed system has a tolerable excess energy generation and has maximum uptime without having much shortage.

Fig. 17 shows the monthly electricity generation according to each component of the hybrid system. It shows that the micro-hydro generator generated according to its resource and the rest power is compensated by the PV-battery system and diesel generators. The operation strategy determines that when the micro-hydro and PV generators are able to meet the load demand, the diesel generators are off. When the load is higher than the capacity of micro-hydro/PV system, the 5 kW diesel generator compensates the excess load and when 5 kW generator is not enough to handle the excess load, the 10 kW generator starts operating. This strategy is automatically adopted by HOMER to minimize the fuel cost and provide the optimum solution. Fig. 18 shows the state of charge of the battery bank. The figure proves that even after discharging its energy to the load it can maintain its state of charge within the specified range (40–80%). In winter, from October to January, when the load is low the battery has higher charge capacity, although the solar radiation is not very high.

5.5. Results analysis and discussion

From Table 8 it can be demonstrated that the hybrid plant designed with micro-hydro/diesel generators illustrated in Section 5.3 has the best economy in terms of initial cost, net present cost and cost of energy. However, PV/micro-hydro/diesel with battery backup scheme is superior in terms of O&M cost, excess electricity

generation, capacity shortage, fuel cost as well as pollutant emission. Other configurations are not competitive in terms of the costs. Some of them have larger environmental pollutant emission constraints. The comparison of emission of pollutants is given in Table 9. The proposed hybrid structure also has the pollutant gas emission, but it is the lowest of all the systems. Moreover, the process requires the lowest amount of fuel and the maintenance cost is also the minimum of all systems which is ideal for rural implementation.

6. Conclusion

The system introduced in the above sections was based on renewable energy resources available in the southern area of Bangladesh. A system consisting PV, micro-hydro with battery backup and diesel generator was introduced and simulated by the HOMER software. The simulation result indicates that compared to other combinations of energy sources micro-hydro/diesel and PV/micro-hydro–Battery/Diesel hybrid system are competitive for that particular place. The micro-hydro/diesel system is cost effective in terms of capital cost, maintenance cost, as well as net present cost and cost of energy. However, in terms of fuel cost, net operating cost, emission and efficiency PV/micro-hydro/Battery/Diesel system is better and suitable. The results show that, compared to only diesel driven system, the hybrid system is 27% cheaper in terms of NPC. Moreover the COE is only 0.206 \$/kWh in the hybrid system. This cost is almost about 28% cheaper than the diesel system.

This article contributes to the knowledge of RE potentiality by revealing the suitable usability and prospects of RE resources to the government and other local or international investors in Bangladesh. Furthermore, it demonstrates a local-oriented analysis of hybrid power system viability for the industrial operators and other interested parties in Bangladesh by emphasizing what key drivers need to be focused. Cost-effectiveness of the proposed system and the possibility of reducing diesel dependency in electricity market of Bangladesh were discussed as well in the study. There are several issues with hybrid power generation, such as load demand increase, generation faults, bus voltage control, hourly based intermittent performance of components, power sources synchronism and diesel generator dispatch complexity. To implement the hybrid system these issues should be analyzed. Several tools such as Hybrid2, HOGA, Simulink can simulate and analyze these and other technical constraints. In this paper only economic aspects are discussed as others are out of scope for HOMER. Finally, the motivation of this study was to encourage people to reduce dependency on fossil fuels as well as promote using renewable energy.

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References

- [1] Fraenkel P, Paish O, Bokalders V, Institute SE, Harvey AP. Micro-hydro power: a guide for development workers. United Kingdom: Intermediate Technology Publications; 1991.
- [2] Nouni M, Mullick S, Kandpal T. Techno-economics of micro-hydro projects for decentralized power supply in India. *Energy Policy* 2006;34:1161–74.
- [3] Jamil A. Biogas and cattle organs: an alternative significant source of energy for sustainable development in rural Bangladesh. 2008 [cited October, 2, 2014]; Available from: <http://urn.kb.se/resolve?urn=urn:nbn:se:sh:diva-1617>.
- [4] Rofiqul Islam M, Islam MR, Beg MRA. Renewable energy resources and technologies practice in Bangladesh. *Renew Sustain Energy Rev* 2008;12:299–343.
- [5] Barkat A, Khan S, Rahman M, Zaman S, poddar A, Halim S, et al. Economic and social impact evaluation study of rural electrification program in Bangladesh: HDRC. Dhaka: Human Development Research Center; 2002.
- [6] Chowdhury N, Reza SE, Nitol TA, Mahabub AA. Present scenario of renewable energy in bangladesh and a proposed hybrid system to minimize power crisis in remote areas. *Int J Renew Energy Res* 2012;2:280–8.
- [7] Hasan F, Hossain J, Rahman M, Ar Rahman S. Design and development of a cost effective urban residential solar PV system [Master thesis]. Bangladesh: Brac University; 2010.
- [8] Mondal MS, AKMS Islam, Madhu MK. Spatial and temporal distribution of temperature, rainfall, sunshine and humidity in context of crop agriculture. In: IoWaF, editor. Management. Dhaka, Bangladesh: Bangladesh University of Engineering and Technology; 2012.
- [9] Micro hydro interventions 2014 [cited May, 2, 2014]; Available from: http://www.lged-rein.org/micro_hydro_intervention.php.
- [10] Ali T, Faruk MO, Gupta SD, Hasan K. Perspective and prospect of tidal energy in Bangladesh.
- [11] Mahbubuzzaman M, Islam MS, Rahman MM. Harnessing tidal power. *The Daily Star*; 2010.
- [12] Tide table: Chittagong, Bangladesh. 2014 [cited October, 5, 2014]; Available from: <http://tides.mobilegeographics.com/calendar/year/1231.html>.
- [13] Local selling price of petroleum products in Bangladesh. 2014 [cited November, 15, 2014]; Available from: <http://www.bpc.gov.bd/contactus.php?id=39>.
- [14] Population and housing census. Bangladesh bureau of statistics; 2011. p. 27–30.
- [15] Ngan MS, Tan CW. Assessment of economic viability for PV/wind/diesel hybrid energy system in southern Peninsular Malaysia. *Renew Sustain Energy Rev* 2012;16:634–47.
- [16] Tijani HO, Tan CW. Techno-economic analysis of hybrid photovoltaic/diesel/battery off-grid system in northern Nigeria. *J Renew Sustain Energy* 2014;6 (033193):1–20.
- [17] Sheilla M, Tan CW, Lim CS. Techno-economic analysis of a photovoltaic-fuel cell grid-connected hybrid energy system. *Int Rev Modell Simul (IREMOS)* 2014;7:65–75.
- [18] Nandi SK, Ghosh HR. A wind–PV–battery hybrid power system at Sitakunda in Bangladesh. *Energy Policy* 2009;37:3659–64.
- [19] Rehman S, Al-Hadhrani LM. Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. *Energy* 2010;35:4986–95.
- [20] Rehman S, Alam MM, Meyer JP, Al-Hadhrani LM. Feasibility study of a wind–pv–diesel hybrid power system for a village. *Renew Energy* 2012;38:258–68.
- [21] Margeta J, Glasnovic Z. Theoretical settings of photovoltaic–hydroenergy system for sustainable energy production. *Sol Energy* 2012;86:972–82.
- [22] Wazed MA, Ahmed S. Micro hydro energy resources in Bangladesh: a review. *Aust J Basic Appl Sci* 2008;2:1209–22.
- [23] Lal DK, Dash BB, Akella AK. Optimization of PV/wind/micro-hydro/diesel hybrid power system in HOMER for the study area. *Int J Electr Eng Inform* 2011;3:307–25.
- [24] Manwell JF, Rogers A, Hayman G, Avelar CT, JG. M. Hybrid 2 – a hybrid system simulation model: theory manual amherst. MA: University of Massachusetts; 1998.
- [25] Dufo López DR, Agustín DJLB. HOGA user manual. Spain: University of Zaragoza; 2012.
- [26] 265W solar panel Mitsubishi PV-MLE265HD mono. 2014 [cited May, 10, 2014]; Available from: <http://www.freecleansolar.com/265W-solar-panel-Mitsubishi-PV-MLE265HD-mono-p/pv-mle265hd.htm>.
- [27] Ampair DRK HT. 2014 [cited May, 10, 2015]; Available from: <http://www.boost-energy.co.uk/>.
- [28] Surrrette 6-CS-25PS solar battery. 2014 [cited May, 10, 2015]; Available from: <http://www.wholesalesolar.com/products.folder/battery-folder/Surretterolls.html>.
- [29] SPV1020 Interleaved DC–DC boost converter with built-in MPPT algorithm. 2014 [cited May, 10, 2015]; Available from: http://www.st.com/web/catalog/sense_power/FM142/CL1810/SC1517/PF250769#.
- [30] Solectria PVI-10kW-208VAC. [cited October, 6, 2014]; Available from: http://www.solar-catalog.com/inverter_m_comm_solectria.html.
- [31] 5 kw changchai diesel generator. [cited November, 25, 2014]; Available from: http://www.alibaba.com/product-detail/Low-price-5kw-changchai-diesel-generator_534115932.html?s=p.
- [32] 10 kw Efficient power machine super silent power diesel generator. [cited November, 25, 2014]; Available from: http://www.alibaba.com/product-detail/10kw-Efficient-power-machine-super-silent_555874598.html?s=p.

- [33] Renewable energy cost analysis: biomass for power generation. International Renewable Energy Agency. 2012;1. p. 1–49.
- [34] Abdilahi AM, Yatim AHM, Mustafa MW, Khalaf OT, Shumran AF, Nor FM. Feasibility study of renewable energy-based microgrid system in Somaliland's urban centers. *Renew Sustain Energy Rev* 2014;40:1048–59.
- [35] Lau KY, Yousof M, Arshad S, Anwari M, Yatim A. Performance analysis of hybrid photovoltaic/diesel energy system under Malaysian conditions. *Energy* 2010;35:3245–55.
- [36] AL_Kababjie M, Hamdon WH. Performance evaluation study of hybrid generation system (micro hydro+ diesel) in iraqi remote rural electrification. *Al-Rafadain Eng J* 2013;21:32–41.
- [37] Bala BK, Siddique SA. Optimal design of a PV-diesel hybrid system for electrification of an isolated island-Sandwip in Bangladesh using genetic algorithm. *Energy Sustain Dev* 2009;13:137–42.