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Article

Decentralized Renewable Hybrid Mini-Grids for Sustainable Electrification of the Off-Grid Coastal Areas of Bangladesh

Majbaul Alam [1] and Subhes Bhattacharyya [2,*]

[1] School of Engineering and Sustianable Development, De Montfort University, Leicester LE1 9BH, UK; majbaalam@yahoo.co.uk
[2] Institute of Energy and Sustainable Development, De Montfort University, Leicester LE1 9BH, UK
* Correspondence: subhesb@dmu.ac.uk; Tel.: +44-116-257-7975

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Abstract: Lack of access to energy is considered as a serious bottleneck for the socio-economic development of Bangladesh. Despite earning recognition for promoting solar home systems, most of the rural areas and remote islands of the country still remain non-electrified due to very high unit cost and low quality of electricity from solar home systems (SHS) coupled with only few hours of restricted usages in the evening. Considering the resource potential and demand characteristics at the local level, the present study investigates the hybrid renewable mini-grid approach as a possible solution for universal electricity access in the country. Using Hybrid Optimisation of Multiple Energy Resources (HOMER) simulation model, the study, covering the whole coastal region of Bangladesh, shows that it is possible to offer a much better quality electricity for 12 h to 18 h a day for as low as USD 0.29–USD 0.31/kWh. Hybrid models suggested in this study can be replicated along the coastal belt and remote islands to obtain maximum diffusion of this technology and hence universal electrification.

Keywords: hybrid mini-grids; coastal Bangladesh; hybrid optimisation of multiple energy resources (HOMER); off-grid electrification

1. Introduction

The energy poor, at the bottom of the economic pyramid (BOP), are unlikely to get the benefits of globalization without having access to the products and services that represent modern day quality standards. Per capita electricity consumption in Bangladesh (259 kWh) is one of the lowest in the world [1]. Currently, the actual generation capacity is 7200 MW, although the installed generation capacity is 9000 MW [2]. According to the National Energy Policy of Bangladesh, the projected demand of electricity in 2020 is 17,580 MW [3]. A national grid covers mostly the urban areas with large industrial and domestic loads leaving the rural areas with either very poor or no supply. Moreover, as the country is crisscrossed by numerous rivers and the population distribution in rural areas is uneven, the grid electrification in many parts of Bangladesh is both difficult and expensive. Only about 40% of rural households have access to grid electricity [4] and the supply is very unreliable.

The coastal areas of Bangladesh (Figure 1) including nineteen administrative districts featuring approximately 270 km coastline are some of the most deprived parts of the country with a disproportionately low level of supply of electricity. Many remote coastal villages and all islands off the coast of Bay of Bengal do not have any grid electricity supply. To improve the rural electrification rate Bangladesh government has been trying to implement renewable energy resources and technologies. The objective of its "final renewable energy policy 2008" [5] is to harness the potential of renewable energy resources and dissemination of technologies especially in the rural areas by encouraging and facilitating both public and private sector investment, hence to promote clean energy with a set target of achieving ten percent of total energy demand from the renewable sources by 2020. Through this policy, government is committed to formulate the way out to attract huge investment in renewable energy projects to substitute non-renewable energy supplies and scale up contributions of existing renewable energy based electricity productions.

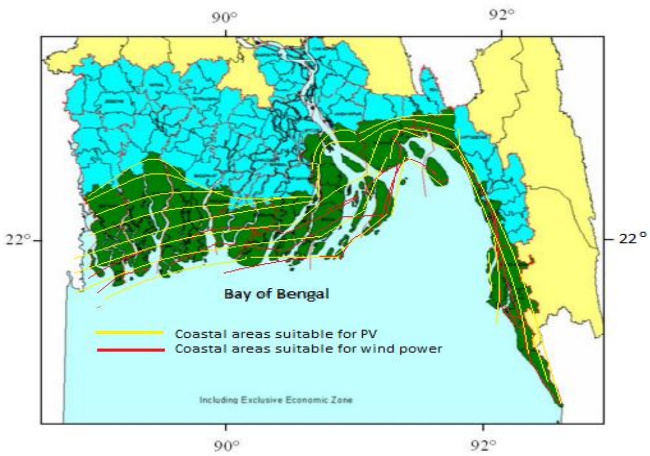


Figure 1. Coastal region of Bangladesh (green areas) showing PV and wind power potential areas (Source: Modified from Khan *et al*. [6]).

Bangladesh has achieved a large success in using standalone solar home systems (SHS) as part of its initiative to use renewable sources to offer more access to electricity. Two million SHS have been installed so far to serve 8.25 million people in the off-grid areas [7] and the average diffusion rate of SHS is 50,000 units per month [8], which is considered the fastest SHS growth rate in the world. This renewable energy technology (RET) has been promoted in the market by using different financial packages like, subsidies and soft loans. At present, the total installed capacity is around 94 MW through the SHSs already installed in the country [9]. Quality of electricity produced by the SHS and the daily duration of supply restrict the users from the many benefits of modern electricity and the unit cost is much higher compared to the grid option [10]. Even with the recent falling price of solar PV panels, the cost of electricity in a SHS is around USD 0.8–1.10 per kWh [11], which is considered very high by any standard.

However, in recent times, local grid-based electricity supply has received global attention and studies by the International Energy Agency (IEA) [12] and World Bank [13] suggest that such mini-grids could cater for 60% of electrification demand in the future. However, despite having various renewable energy resources available, Bangladesh has not adopted mini-grids to a significant level. Only a few pilot projects exist (*i.e.*, Sunamganj Solar mini-grid, Sandwip solar-diesel hybrid mini-grid, Thanchi Solar mini-grid, Kutubdia wind mini-grid) [14] and it is important to explore the techno-economic attractiveness of such an option in the local context. Accordingly, this paper presents a systematic study of the coastal region of Bangladesh using HOMER simulation software to identify the hybrid renewable energy technologies for mini-grid based supply.

The paper is organized as follows: Section 2 presents the mini-grid options; Section 3 outlines the methodology while Section 4 contains the results. Discussion are presented in Section 5 and final recommendations are presented in Section 6.

2. Mini-Grid Options

Studies [15–19] showed that hybrid power systems could be more reliable and cheaper than single source energy systems for decentralized mode of operation. Kumar and Manoharan [20] indicate positive dissemination of hybrid mini grid systems in different climatic zones of Tamil Nadu, India where existing power supply through the main grid is unstable. Study conducted for the rural and semi-urban northern part of Nigeria suggests that decentralized hybrid systems are a better and cheaper option in long run compared to diesel generators [21]. The foreseeable limitations and possibilities associated with the hybrid mini-grids have been highlighted in different literatures [22–31]. Only a few works [32–37] exist in this field in Bangladesh and the limitations and possibilities of hybrid mini grids are still to be explored.

Given that local resources, enabling policy environment and village-level information are essential to any analysis of mini-grid based electrification, these are considered below for the coastal areas of Bangladesh.

2.1. Renewable Resources

The global horizontal irradiance (GHI), based on the measured data, theoretical model derived data and satellite image derived data, shows that the average solar global radiation in Bangladesh is around 4.255 kWh/m^2/day [38]. Based on solar energy resources over the country it can be said that most of the solar energy extracting systems can be used for power generation. To use wind energy for power generation in Bangladesh, the areas are limited mostly to the coastal regions, *i.e.*, Cox's Bazar, Teknaf, coastal belt of Chittagong, Saint Martin Island, Kutubdia, Moheskhali, lower parts of Barisal, Bhola, Bagherhat, Noakhali and other islands like Hatia and Swandip (Figure 1). There is only a little potential of wind energy resources at a very high altitude in the north of the country. The south and southwesterly wind blows over Bangladesh from March to September with a monthly speed up to 6 m/s [39]. The coastline and the islands along the coastline offer suitable conditions for wind power generation.

2.2. Policy Support

The draft renewable energy policy (2002) of Bangladesh [40] and the current policy [5] have clearly developed an Investment and Fiscal Incentive guideline, where Sustainable Energy Development Authority (SEDA) formulates fiscal incentives and considers subsidies for the investments in the renewable energy projects and assists investors in locating the project(s) and acquiring land for this purpose. Moreover, the Remote Area Power Supply System (RAPSS) policy offers connection fee subsidy for increased customer penetration (with connected load less than 300 watt) for a maximum period of seven years and additional subsidized loan to achieve competitive tariff to the investors in the distributed renewable mini-grids. Infrastructure Development Company Limited (IDCOL) facilitates the techno-economic matters for the investors in the remote area renewable energy projects. IDCOL has created a subsidy fund to be invested in decentralized hybrid mini-grids and up to maximum of 60% capital subsidies can be offered in this field.

2.3. Mini-Grid Implementation

Average number of households in rural Bangladesh is around 200 per village [41], which is suitable for micro/mini grid operations [42]. Bangladesh can take inspiration from the example of India where densely populated remote areas are served by decentralized renewable energy systems providing electricity to households via micro-grids which have been considered one of the most economically feasible options [43]. With the support from the existing renewable energy policy, people of the off-grid areas of the coastal belt can be provided with reliable electricity using the renewable mini-grid options. However, the major challenges in the implementation of decentralized renewable hybrid mini-grids in coastal rural areas and islands include restricted consumption pattern (time and load) by the end users, uncertainty of seasonal demand, expensive storage, different operation-management arrangements for individual micro-grids, lack of expert manpower, security of the distribution network and restricting loss and theft.

3. Methodology

To suggest the most sustainable techno-economic hybrid mini-grid models for the coastal regions including the islands we have tested ten different system configurations having different load scenarios. All of these models are briefly described initially and two optimal models are discussed elaborately and their results are analyzed in detail. For solar radiation data in the study areas the National Renewable Energy Laboratory (NREL), USA database has been used applying the HOMER resources menu and the monthly average solar radiation in the study area is shown in Figure 2. Wind resources were derived from different studies [6,32,44,45] based on the field data collected by Bangladesh Meteorology Department (BDM) at different times and average wind speed is presented in Figure 3. Different load profiles (domestic only, domestic and commercial combined and managed load) have been formulated using socio-economic pattern and current trend of energy consumptions in the study areas. Domestic and combined load profiles are built on the usual life styles of the people in the study areas, *i.e.*, domestic consumers charge mobile phones and play audio devices in the morning, shops run live TVs only in evening and farmers use irrigation pumps in the morning. The managed load profile is based on the assumption that if consumers are let to make informed decision on the consumption schedule of electricity, the load demand can be synchronized with the power production schedule of different components of the hybrid systems. For example, shops can run recorded TV for extended hours and farmers can use pumps only when systems produce excess power based on the natural resource supply. Managed load profile has been designed to achieve best hybrid system efficiency.

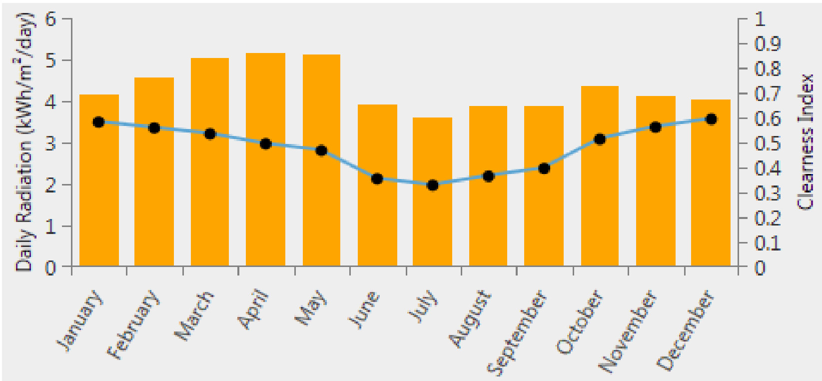


Figure 2. Monthly average solar radiation in the study areas.

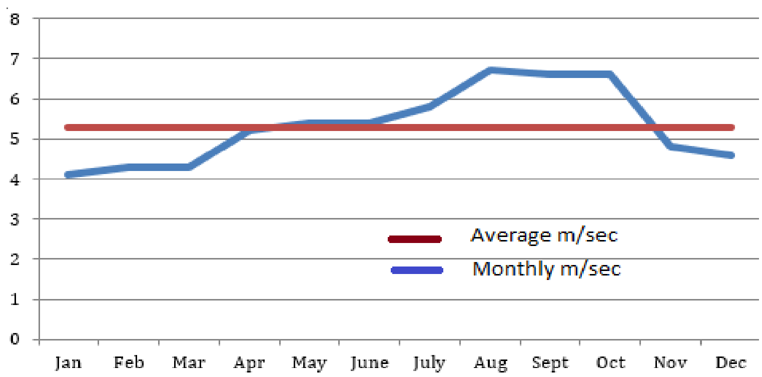
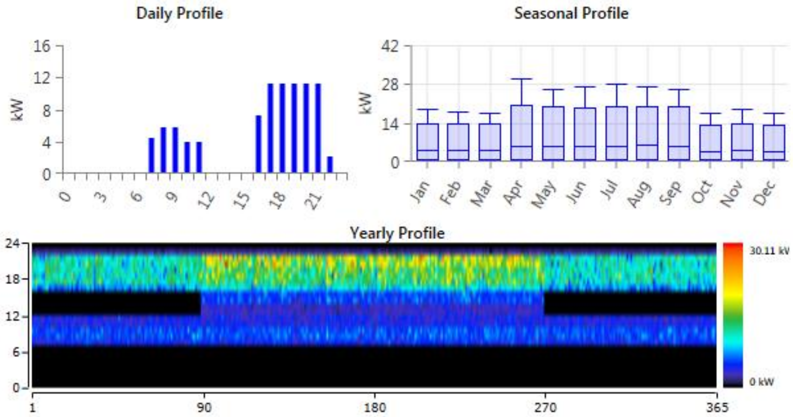
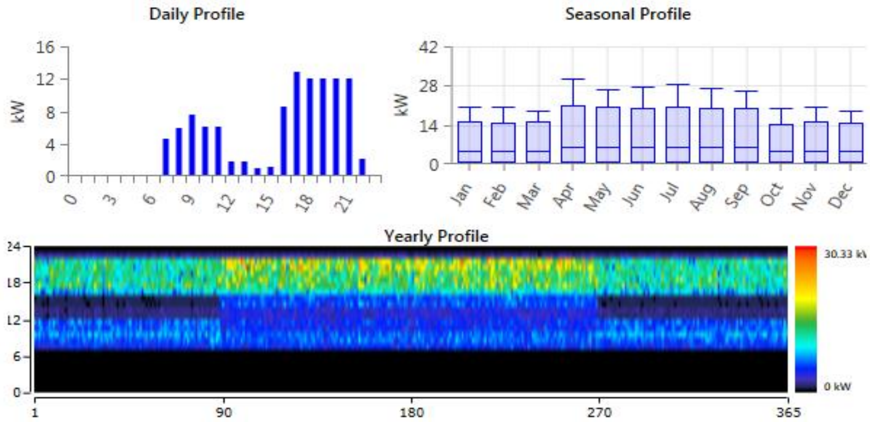


Figure 3. Monthly wind profile used in the study areas.

Three bigger load profiles applied to serve various combinations of 200 households, 15 businesses, 5 irrigation pumps and 2 cottage factories for 12 h (Figure 4a) and 16 h (Figure 4b,c) a day termed as "Load profile 1, 2 and 3" serving the maximum load of 30.11 kW, 30.33 kW and 30.19 kW, respectively. On the other hand, two smaller load profiles for two different durations and load patterns serving 6 h domestic load only (Figure 4d) and 15 h combined domestic and commercial load (Figure 4e) termed as "Load profile 4 and 5" serving maximum load of 4.61 kW and 4.62 kW respectively were applied to this study. Seasonal domestic, commercial and agricultural or other small industrial loads have been separated for the three bigger load profiles (load profile 1, 2 and 3) to ensure better simulation efficiency (Table 1).



(**a**)



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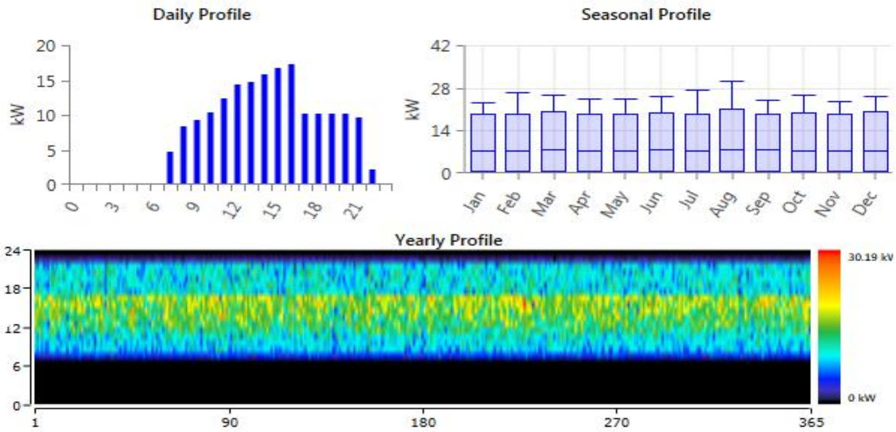
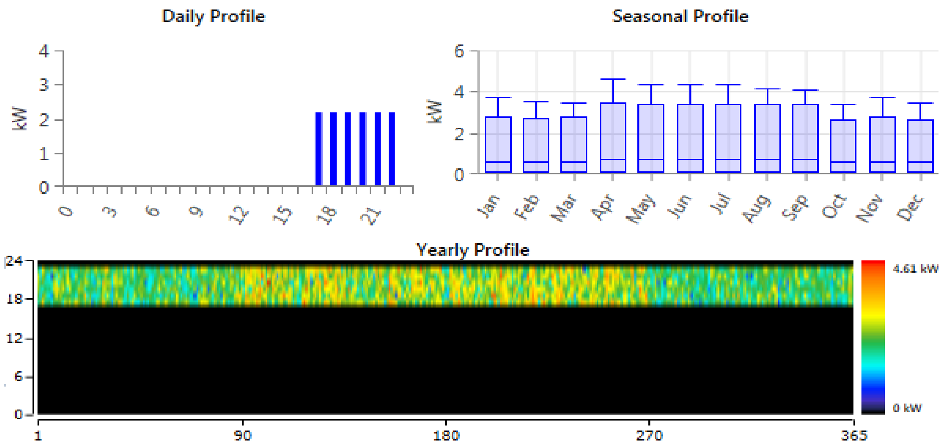


(**c**)

Figure 4. *Cont*.



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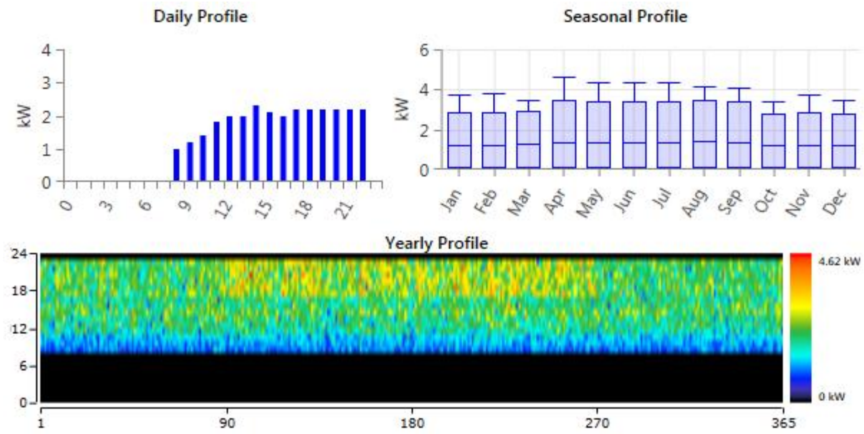


(**e**)

Figure 4. (**a**) Domestic (12 h) load profile; (**b**) Domestic and commercial combined (16 h) load profile; (**c**) Domestic, commercial and agricultural/industrial managed load (16 h) profile; (**d**) Smaller (6 h) load profile; (**e**) Smaller (15 h) load profile.

For economic analysis the fixed capital cost, cost of equipment, maintenance, fuel cost and applicable subsidies were considered. Two different capital investment approaches were applied; the first approach is 50% soft loan with 5% interest rate and 50% investor equity and the second one is 40% capital subsidy provided by IDCOL, 30% soft loan with 5% interest and 30% investor's equity. Fixed capital costs of USD 25,000 and USD 15,000 have been estimated for the larger (30 kW + peak) and smaller projects (4 kW + peak) to cover the cost of power station building, equipment installations, distribution network and customer metering. Generic flat panel PV, diesel generator, generic 3 kW and 1 kW wind turbines, lead acid battery (6 V, 225–360 Ah) and converter's initial costs are estimated as USD 600/kW, USD 500/kW, USD 8000 and USD 3000, USD 175/battery and USD 250/kW respectively and the replacement costs as USD 400/kW, USD 400/kW, USD 6000 and USD 2000, USD 150/battery and USD 200/kW. All the costs were calculated based on the availability of the equipment in the local market (Component price compared with the current market price offered by two major supplies (or system installers) in Bangladesh: Navana Renewables and Rahim Afroze Renewable energy) while complying with quality standard required by IDCOL. The total project life has been used as 25 years for lifecycle cost analysis along with assumed life of PV 25 years, generator 20 years, wind turbine 20 years, battery 10 years (depends on actual state of charge) and converter 25 years. Cost of diesel estimated as USD 0.80/L as a primary fuel for the generator.

Table 1. Hourly load profile (April–September and October–March).

Hourly Load (kW)	07–08 a.m.		08–09 a.m.		09–10 a.m.		10–11 a.m.		11–12 p.m.		12–01 p.m.		01–02 p.m.		02–03 p.m.		03–04 p.m.		04–05 p.m.		05–06 p.m.		06–07 p.m.		07–08 p.m.		08–09 p.m.		09–10 p.m.		10–11 p.m.	
BULB **April–September** *October–March*	*0.5*	**0.5**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*4.0 +* 0.3	**4.0 +** 0.32	*4.0 +* 0.3	**4.0 +** 0.32	*4.0 +* 0.3	**4.0 +** 0.32	*4.0 +* 0.3	**4.0 +** 0.32	*4.0 +* 0.3	**4.0 +** 0.32	*0.3*	**0.3**
RADIO **April–September** *October–March*	*3.5*	**0.35**	*4.0 +* 0.20	**4.0 +** 0.20	*4.0 +* 0.20	**4.0 +** 0.20	*4.0 +* 0.20	**4.0 +** 0.40	*4.0 +* 0.20	**4.0 +** 0.40	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	*2.4 +* 0.36	**2.4 +** 0.36	*2.4 +* 0.36	**2.4 +** 0.36	*2.4 +* 0.36	**2.4 +** 0.36	*2.4 +* 0.36	**2.4 +** 0.36	*2.4 +* 0.36	**2.4 +** 0.36	*2.4 +* 0.36	**2.4 +** 0.36	-	-
MOBILE **April–September** *October–March*	*0.5*	**0.5**	*1.7*	**1.70 +** 1.10	*1.7 +* 0.22	**1.70 +** 1.10	0.22	0.12	*0.22*	0.12	*0.12*	0.12	*0.12*	0.12	*0.10*	0.12	*0.10*	-	-	-	-	-	-	-	-	-	-	**0.08**	-	**0.08**	-	-
FAN **April–September** *October–March*	-	-	-	-	-	-	-	-	-	**0.24**	-	**3.20 +** 0.24	-	**3.20 +** 0.24	-	**5.60**	-	**5.60**	-	**0.24**	-	**2.40 +** 0.24	-	**3.20 +** 0.24	-	**3.20 +** 0.24	-	**5.6**	-	**5.6**	-	-
TV **April–September** *October–March*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.12	-	*4.8 +* 0.24	**4.8 +** 0.12	*4.8 +* 0.24	**4.8 +** 0.24	*4.8 +* 0.24	**4.8 +** 0.24	*4.8 +* 0.24	**4.8 +** 0.24	*4.8 +* 0.24	**4.8 +** 0.24	*4.8 +* 0.24	**4.8 +** 0.24	*1.8*	-
PUMP **April–September** *October–March*	-	-	-	-	*1.50*	-	*1.50*	-	*1.50*	-	*1.50*	-	*1.50*	-	*0.75*	-	*0.75*	-	*0.75*	-	*0.75*	-	-	-	-	-	-	-	-	-	-	-

Domestic Load, CommercialLoad, Agricultural Load (kW)

The "Hybrid Optimization Model for Electric Renewables" (HOMER) [46] micro-grid designing software (pro version) has been used in this study to design the hybrid systems configuration consisting different components, *i.e.*, solar PV, wind turbine, diesel generator and storage devices. This software has successfully been used around the world by many researchers [37,47–50]. HOMER performs three principal tasks (simulation, optimization and sensitivity analysis) while suggesting the suitable system designs. HOMER suggests the best optimized model design for the given specific load, resources, economic inputs, system control features, constraints and sensitivity variables. However, it also suggests the lifecycle cost of the system as the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, having future cash flows discounted to the present. Although the levelized cost of energy (LCOE) is often a convenient metric with which to compare the costs of different systems, HOMER uses the total NPC instead as its primary economic figure of merit. In its optimization process, HOMER ranks the system configurations according to NPC rather than levelized cost of energy.

HOMER uses the following equation to calculate the total net present cost:

$$\mathrm{C_{NPC}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{CRF}\left(\mathrm{i}, \mathrm{R_{proj}}\right)} \tag{1}$$

where, $\mathrm{C_{ann,tot}}$ is the total annualized cost, i the annual real interest rate (the discount rate), $\mathrm{R_{proj}}$ the project lifetime, and CRF (i,N) is the capital recovery factor, given by the equation:

$$\mathrm{CRF}(i, \mathrm{N}) = \frac{i\,(1+i)^{N}}{(1+i)^{N} - 1} \tag{2}$$

where, i is the annual real interest rate and N is the number of years. HOMER uses the following equation to calculate the levelized cost of energy (COE):

$$\mathrm{COE} = \frac{C_{\mathrm{ann,tot}}}{E_{\mathrm{prim}} + E_{\mathrm{def}} + E_{\mathrm{grid,sales}}} \tag{3}$$

where, $C_{\mathrm{ann,tot}}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{\mathrm{grid;sales}}$ is the amount of energy sold to the grid per year (*for this study* $E_{\mathrm{grid;sales}}$ *value is zero* as systems considered here are not grid connected or ready to grid connect). The levelized cost of energy is therefore the average cost per kWh of useful electrical energy produced by the system but not the amount of energy utilized by the end users.

4. Results

Homer analyzed around 9216 simulations for each of the ten different load profiles and for different hybrid system configurations having various sensitivity variables and economic constrains (*i.e.*, capacity shortage, battery life, fuel usages, interest rate, capital subsidy, excess energy) and presents around 65 feasible models. The optimal Hybrid Mini-Grid (HMG) system configurations for designed load profile 1, 2, 3, 4 and 5 suggested by HOMER are presented in detail in Table 2. For load profile 1, where only domestic load (110.06 kWh/day) is applied, the proposed HMG 1 and 4 present the highest unit cost of electricity between USD 0.579–USD 0.476 for no capital subsidy and 40% capital subsidy, respectively. While the commercial load of 12.593 kWh/day added to the regular domestic load representing "load profile 2" for the current study the HMG 2 and 5 present the cost of electricity as USD 0.542–USD 0.508 and USD 0.466–USD 0.428 for no subsidy and 40% subsidized capital investment. However, applying the managed load profile with extended commercial and small industrial load of 45.358 kWh/day the lowest unit COE of USD 0.368–USD 0.366 and USD 0.316–USD 0.29 achieved through HMG 3 and 6 using no subsidy and 40% subsidy, respectively. By using managed load profile HMG 6 and 3 produce only 17% and 19% of excess electricity through out the year in compare to 37% and 35% in HMG 1 and 7, respectively.

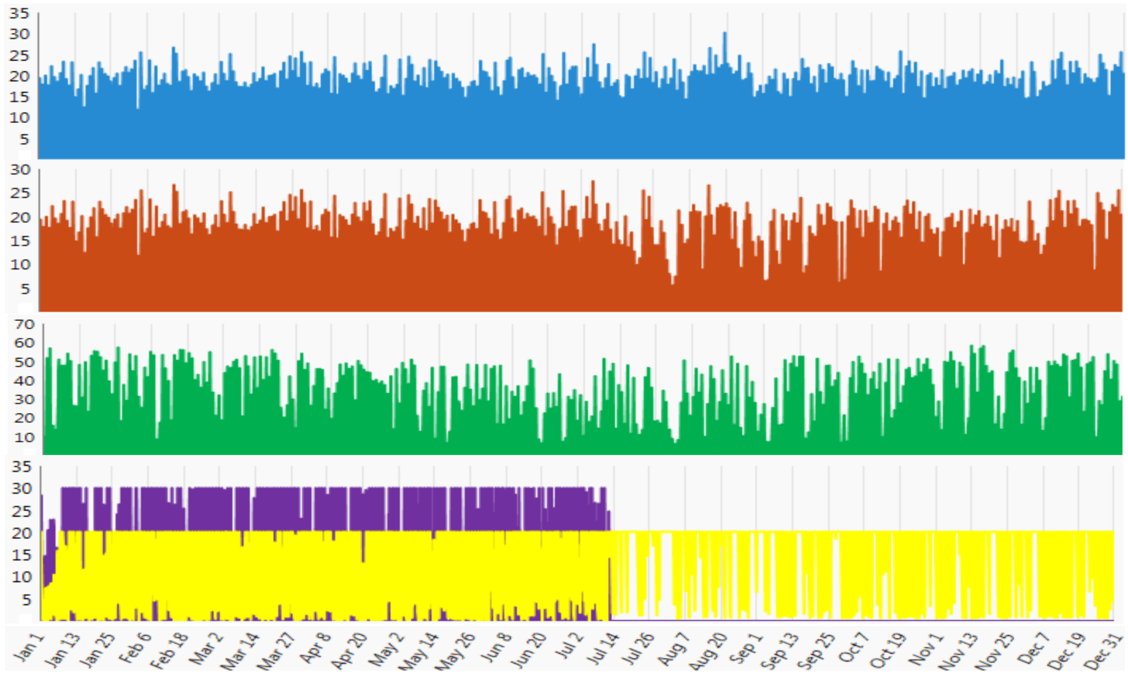
The HMG 7, 8, 9 and 10 with relatively much smaller load (load profiles 4 and 5) present the COE very high in comparison to the bigger load profiles studied. Different system configurations (HMG 7 and 8) operating only 6 h in the evening serving 14.7 kWh/day represent COE as high as USD 1.39–USD 1.34 for no capital subsidy. However, the same HMGs serving the same load profile with 40% capital subsidy supply electricity for USD 1.14–USD 1.10. HMG 8 and 10 with different system configurations applying relatively higher combined load of 30.5 kWh/day over 15 h a day deliver electricity at a lower price of USD 0.582–USD 0.626/kWh.

Capital subsidy used in this study (40%), showed significant reduction in COE between USD 0.13–USD 0.25/kWh in cases of HMGs with very small loads (HMG7–10, Table 2). On the other hand, same amount of subsidy applied on systems with relatively bigger loads (HMG 1–6; Table 2) reduces the COE ranging from USD 0.05–USD 0.08/kWh.

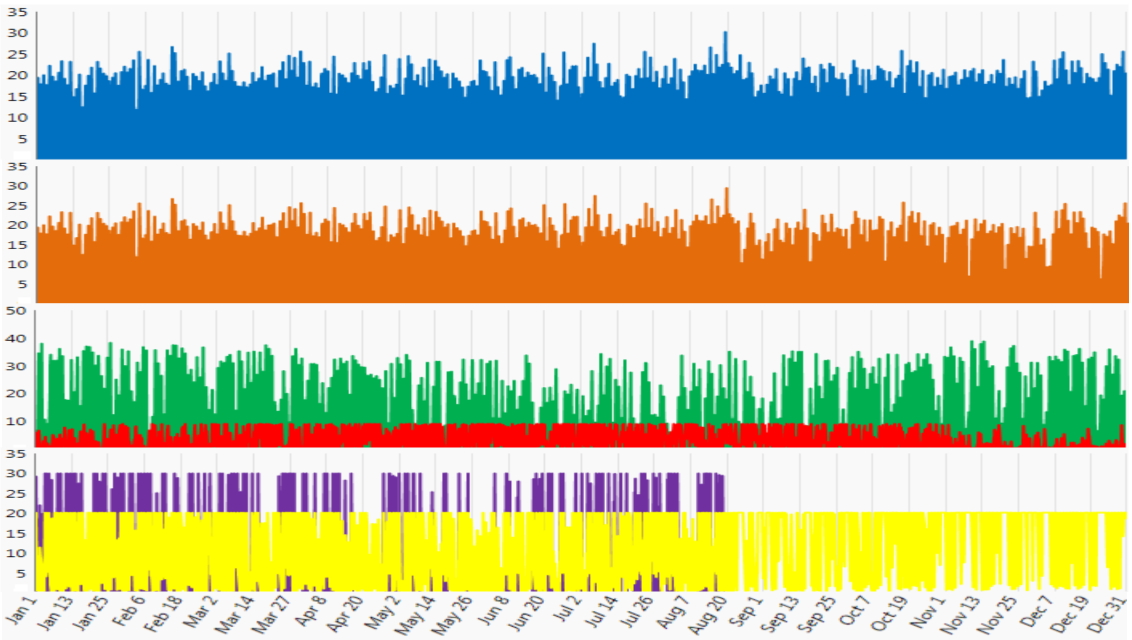
The optimal hybrid systems identified in this study based on the net present cost and COE are HMG 3 and HMG 6 both serving the managed load profile. A detailed time series analysis of these two hybrid systems (Figure 5a,b) indicates clear harmony between primary AC load demand and load served. Capacity shortage is smaller in HMG 6 (6%) than in HMG 3 (8%) as the gap between the load demand and combined power served by different components is very marginal. HMG 6 shows steady performance by all of its components, especially power produced by the wind turbine during the months of August to November, thereby reducing the dependency on generator. Moreover, the synchronized maximum charge state increases the battery life and hence reduces the cost of electricity (Figure 6a,b). The maximum battery life of 4.30 years and 4.84 years achieved in HMG 3 and HMG 6 accordingly. On the other hand equal converter lifetime (8.5 years) was observed for both the hybrid systems. Analyzing the nominal cash flow between two optimal hybrid systems, HMG 3 and HMG 6 (Figure 7a,b) it is clear that HMG 6 offers the best cash flow throughout the project life.

Table 2. Different hybrid mini-grids profile and economic features.

Hybrid Mini Grid (HMG) Architecture and Applied Load Profile	Scaled Load Profile			Load Share kWh/Day		Operating Hours per Day	Initial Capital USD		Cost/ Year	NPC (No Subsidy) × 1000	NPC (Subsidized) × 1000	COE (No Subsidy)/kWh	COE (Subsidized)/kWh	Renewable Fraction (%)	Excess Energy (%)
	Annual Average kWh/d	Scaled Average kW	Scaled Peak kW	Domestic	Commercial		No Subsidy × 1000	Subsidized × 1000							
HMG 1: PV 50 kW, Genset 30 kW, Converter 20 kW, Battery 1 kWh × 80; (10% capacity shortage)															
Load profile 1	110.06	4.59	30.11	110.56	-	12	87	52	13,569	262	227	0.579	0.502	55	37
HMG 2: PV 60 kW, Genset 30 kW, Converter 30 kW, Battery 1 kWh × 80; (8% capacity shortage)															
Load profile 2	122.65	5.11	30.33	110.06	12.59	16	95	57	13,685	273	234	0.542	0.466	60	31
HMG 3: PV 60 kW, Genset 30 kW, Converter 30 kW, Battery 1 kWh × 90; (8% capacity shortage)															
Load profile 3	176.77	7.37	30.19	131.41	45.36	16	92	58	13,387	271	231	0.368	0.316	78	19
HMG 4: PV 40 kW, Genset 30 kW, Converter 20 kW, Battery 1 kWh × 80, Wind G3x3; (8% capacity shortage)															
Load profile 1	110.06	4.59	30.11	110.06	-	12	121	72	12,059	268	228	0.545	0.476	74	31
HMG 5: PV 40 kW, Genset 30 kW, Converter 30 kW, Battery 1 kWh × 90, Wind G3x3; (8% capacity shortage)															
Load profile 2	122.65	5.11	30.33	110.05	12.59	16	109	65	12,632	276	228	0.508	0.428	77	29
HMG 6: PV 40 kW, Genset 30 kW, Converter 30 kW, Battery 1 kWh × 90, Wind G3x3; (6% capacity shortage)															
Load profile 3	176.77	7.37	30.19	131.41	45.36	16	109	65	12,609	287	228	0.366	0.29	84	17
HMG 7: PV 10 kW, Genset 10 kW, Converter 10 kW, Battery 1 kWh × 60; (10% capacity shortage)															
Load profile 4	14.7	0.61	4.61	14.7	-	6	42	25	4161	96	79	1.39	1.14	91	35
HMG 8: PV 10 kW, Genset 10 kW, Converter 10 kW, Battery 1 kWh × 60; (8% capacity shortage)															
Load profile 5	30.5	1.27	4.62	14.7	15.35	12	42	25	4994	107	900	0.744	0.626	73	27
HMG 9: PV 5 kW, Genset 10 kW, Converter 10 kW, Battery 1 kWh × 40, Wind G1x2; (8% capacity shortage)															
Load profile 4	14.7	0.61	4.61	14.7	-	6	44	26	3844	93	76	1.34	1.10	93	31
HMG 10: PV 10 kW, Genset 10 kW, Converter 10 kW, Battery 1 kWh × 60, Wind G1x2; (6% capacity shortage)															
Load profile 5	30.5	1.27	4.62	14.7	15.35	12	50	30	4136	103	83	0.719	0.582	94	24

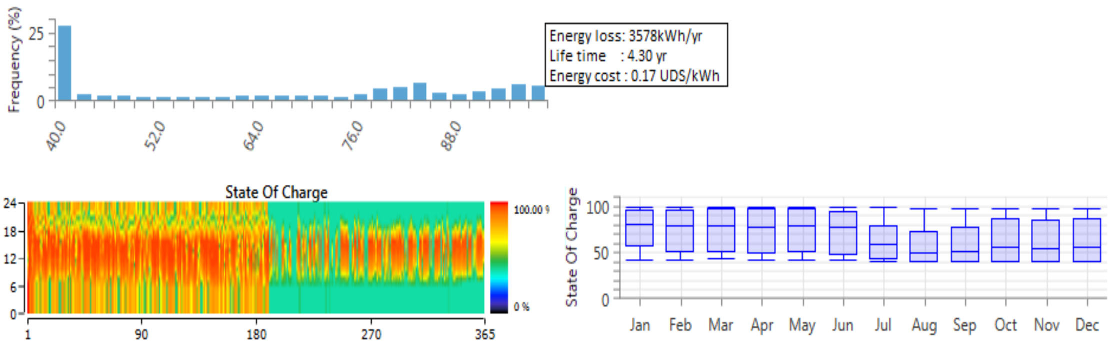


(**a**)

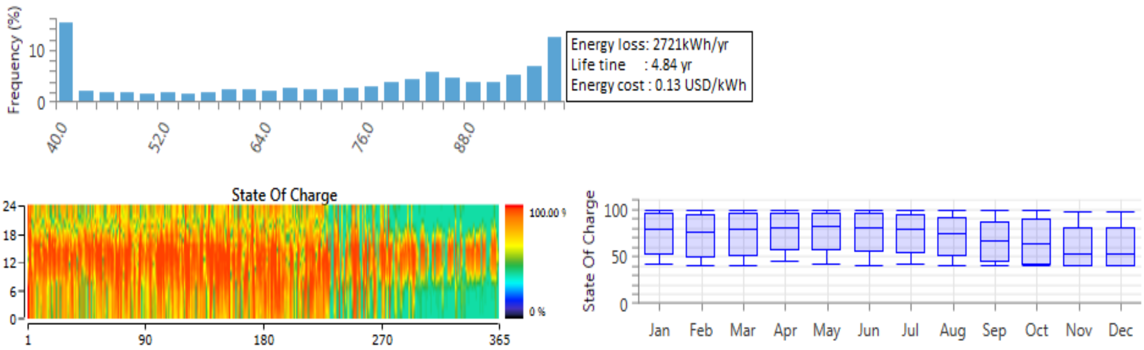


(**b**)

Figure 5. (**a**) HMG 3, time series detail system performance analysis *; (**b**) HMG 6, time series detail system performance analysis *. * All values in kW ■ AC Primary Load ■ AC Primary Load Served ■ PV Power Generation ■ Generator Power Output ■ Battery Maximum Charge ■ Wind Turbine Power Output.

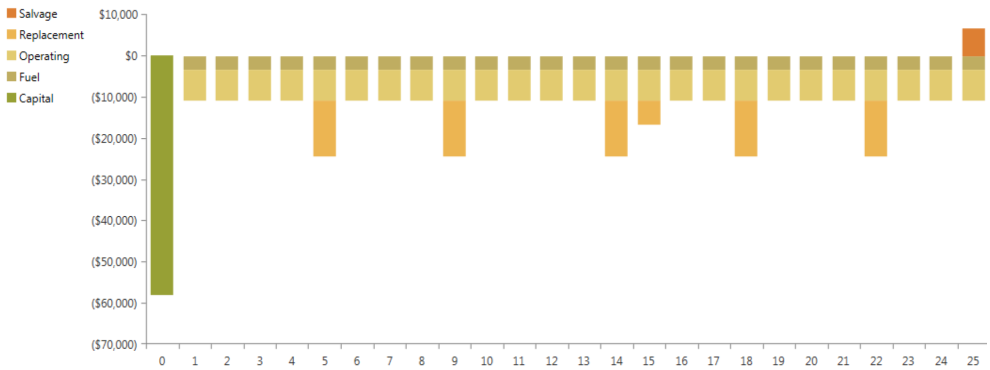


(**a**)

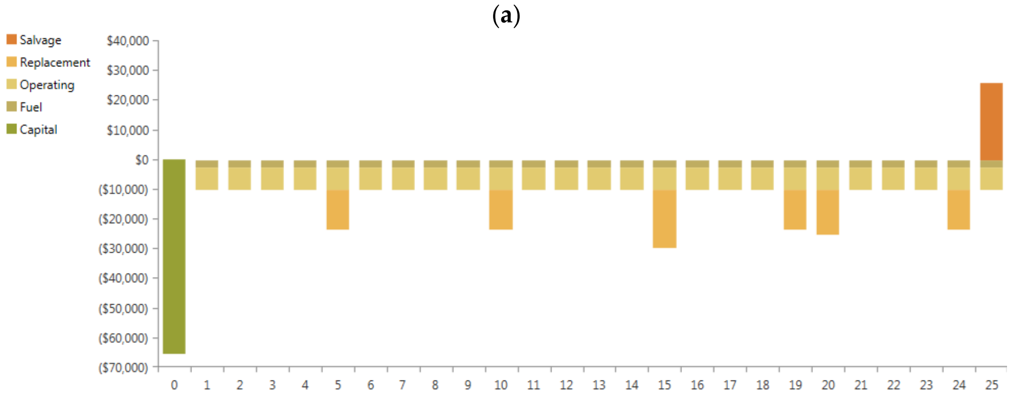


(**b**)

Figure 6. (**a**) HMG 3, battery performance report; (**b**) HMG 6, battery performance report.



(**a**)



(**b**)

Figure 7. (**a**) HMG 3, Nominal cash flow; (**b**) HMG 6, nominal cash flow.

5. Discussion

Availability and the average intensity of solar and wind resources for a specific hybrid system in the proposed study areas are same. Therefore, renewable resources and component combinations for HMGs can be either Solar-diesel generator-battery or solar-wind-diesel generator- battery depending on the location of the project. Hybrid systems with wind turbines can be implemented in areas covered by the thin red line in Figure 1, where wind speed is relatively higher. Study [51] conducted on renewable energy storage systems on small islands show that the combination of wind power and battery storage is less favorable compare to PV-battery hybrid systems as it is uneconomical at low wind speed. Projects serving relatively bigger electrical loads in this study represent better NPC and much cheaper COE.

Tariff is probably the most important element of successful sustainable decentralized hybrid mini-grid implementation. No willingness to pay (WTP) study has been carried out for the decentralized hybrid renewable energy supply in the off-grid areas of Bangladesh. As neither SEDA nor IDCOL decide the retail price of the electricity produced by the private investors using renewable energy sources, a sustainable tariff has to be introduced by the supplier to make the project viable. Rural people in Bangladesh using stand-alone SHS actually pay USD 1.04/kWh [52] and USD 0.60–0.98/kWh for using diesel grid [53] and USD 0.67/kWh for kerosene [54]. It is evident from the most successful 100 kW PV-diesel hybrid system with battery bank in Sandwip, Bangladesh that consumers are willing to pay USD 0.41/kWh of electricity [53]. Therefore, average tariff ranging from USD 0.40–USD 0.45/kWh can be applied for the decentralized hybrid systems in rural Bangladesh, which can guarantee enough profit for the investors producing electricity for USD 0.29/kWh or USD 0.316/kWh from the study under configurations HMG 6 and 3 respectively. Given that they offer electricity at a relatively low cost, these two models of HMGs become candidates for replication in the whole coastal areas of Bangladesh.

6. Recommendations

The optimal hybrid system configurations obtained from the study indicate that cost-effective hybrid mini-grids can be developed for decentralized electricity supply in the coastal areas of Bangladesh. However, an efficient revenue recovery strategy is important to ensure project implementation. Consumers in the mini grid area could be categorized depending on their need and financial capability. For the basic users, a fixed monthly/ weekly charge for usages can be applied. On the other hand medium and large users can be connected with pre-pay or post-pay meters depending on their financial conditions. For commercial usages, *i.e.*, shops, cottage factories *etc.*, a fixed charge can be applied or be fitted with meters as "*pay as you go*" basis.

Smart pricing of electricity is essential, which sets different price for different hours of the day and night depending on the cost of production. Time varying pricing scheme [55] can be a very effective tool for influencing the price responsive end users. "Seasonal tariff set up" is another option to recover the cost of production with varying availability of resources in specific project locations. For agricultural activities, a subsidized tariff may be required, as farmers use highly subsidized diesel for irrigation. In this case private electricity suppliers may request for an extended "*tariff subsidy*" for agricultural activities and receive support from the government.

Regular interactions with the local member of the public will be a prerequisite for better understanding of the consumer need. Local youth can be trained to ensure skilled manpower supply for any future project expansion. However, consumers need to be educated both by the public and private sector for effective and productive use of electricity. Thus social empowerment can be achieved, which in turn will help mass diffusion of renewable mini grids.

Timely maintenance of every equipment and replacement are very important for providing reliable service and acquiring consumer's confidence and loyalty. Any operation and maintenance should be in accordance with the policy guideline. For smart operation remote data monitoring system can be applied. Everyday operational data and resources abundance need to be duly collected and preserved, as this would help both the private investor itself and the policy makers to step forward in mass penetration in this market.

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