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A thorough investigation on hybrid application of biomass gasifier and PV resources to meet energy needs for a northern rural off-grid region of Bangladesh: A potential solution to replicate in rural off-grid areas or not?

Md Shahinur Islam [a, *], Ruma Akhter [b], Mohammad Ashifur Rahman [c]

[a] School of Electrical Engineering, Royal Institute of Technology (KTH), 100 44, Stockholm, Sweden
[b] Postgraduate Program in Renewable Energy, Institute of Physics, University of Oldenburg, 26111, Oldenburg, Germany
[c] Electrical Energy Systems (EES), Eindhoven University of Technology, 5612, AZ, Eindhoven, The Netherlands

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ABSTRACT

Rural electrification is a critical global challenge specifically in developing countries and Bangladesh is no exception. Most of the people live in the rural areas of the country and having no access to grid electricity hindering the development of these areas and the overall progress of the country's economy severely. In this regard, renewable energy based hybrid mini-grid can be a viable solution to ensure access to electricity for all. This paper presents a case study of supplying electricity through hybrid mini-grid to the rural unelectrified areas of the northern region of Bangladesh, and provides an analysis of its business creation, operation and related challenges. The study involves modelling of three alternative configurations for electricity generation with the different combination of solar energy, biomass generator, diesel generator and battery storage resources. Hybrid Optimization Model for Electric Renewable (HOMER) software is used to carry out the techno-economic analysis and identify the optimal off-grid system configuration. The analysis exposed that the per unit cost of electricity from the optimum off-grid supply configuration is much higher than the regulated tariff for grid connected residential consumers and cannot reach grid parity even with the full capital subsidy. However, the cost of off-grid supply is economical than the diesel-only supply option or the cost of owning a solar home system. The analysis further considered different electricity selling tariff to obtain a practical and reasonable payback period to make the proposed hybrid mini-grid system economically worthwhile. From the emission analysis, it is found that the proposed hybrid system would produce 75% lower CO_2 than the existing methods of fulfilling energy needs in the study area.

1. Introduction

World energy demand is constantly on the rising side while the primary energy resources are depleting by leaps and bounds. About 1.3 billion of the world's total population still lack access to electricity where over 80% of them live in rural areas [1]. Bangladesh has the lowermost per capita electric power consumption according to the World Bank's statistics; consumes only 310 kWh which is substantially lower than Asia's average rate of about 451 kWh, and far behind the world's average rate of 3128 kWh [2]. More than 65% people of its population live in rural areas, and most of these rural people who live their life through agricultural activities use kerosene/candles/and dry cell batteries for lighting purpose [3] [4]. About 70% rural population of Bangladesh have no electricity access which means there are few to no industrial actives in those areas, affecting the quality of life while excluding them from national economic development activities [5]. The rural grid of the country is characterized by a relatively lower consumer density and thus it frequently becomes uneconomical to extend electric grid to certain isolated sites [6]. But to ensure the overall development, the country needs to prioritize the socio/economic betterment of these villages, and such development can be boosted through rural electrification [7] [8].

* Corresponding author.
E-mail addresses: msislam4@kth.se (M.S. Islam), ruma.akhter@uni-oldenburg.de (R. Akhter), m.a.rahman@alumnus.tue.nl (M.A. Rahman).

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The economic progress and standard of living of a country are determined by Gross Domestic Product (GDP) and it is significantly influenced by the level of energy consumption. It is estimated that 1% rise in per capita energy consumption creates a growth in per capita GDP by 0.23% and vice-versa [9]. Fig. 1 illustrates the GDP per capita rise vs per capita energy consumption trend in Bangladesh for the period 1990 to 2014. It is notable from the figure that until 2005 the per capita income was somewhat not significant as per capita electricity consumption was also very low during that period. With the per capita income rising substantially in recent years, the rising trend of per capita energy consumption is also clearly visible. The World Bank global report projected 6.8% GDP growth for Bangladesh in 2016–17 and forecasted that the coutry's GDP will continue to rise above 6.5% per annum until 2020 [10]. On the other hand, Power Sector Master Plan Bangladesh (PSMP) 2016 projected a growing rate of the dispatched power demand 6.9% per year from 2015 to 2041, when GDP growth rate will happen at least 6.3% per year during the same period [11]. However, in reality, it has been observed that the electricity demand has been growing over 12%–15% annually [12]. To achieve the projected rate of GDP growth, the country undoubtedly needs to expand its electricity generation capacity.

The state-owned agencies mainly Bangladesh Power Development Board (BPDB), Rural Electrification Board (REB) and Polly-Bidyut Samity (PBS) are involved to supply electricity in rural areas [13]. However, rural electrification has not progressed well due to the transmission, distribution losses and discrepancy between load-demand criteria and consequently, electricity infrastructure of Bangladesh is overburdened with un-widely load-shedding [103]. In this circumstance, off-grid electrification could be a crucial and competent solution rather than extending electricity grid in the rural areas [14]. Solar Home System (SHS) was considered a viable technical option for such off-grid remote areas, particularly for ensuring equitable progress of all areas and different cross-sections of socio-economic groups [15]. However, Rahman and Ahmed (2013) argued that overall rural development in Bangladesh has not been influenced significantly so far even with widespread dissemination of SHSs [16]. SHS is being used vastly in Bangladesh, but often it is incompetent to supply consumers energy demand satisfactorily, and reliably because of resource constraint which is not suitable for small to large-scale industries. Besides, Bhattacharyya (2015) reported that the cost of owning a SHS for rural people is likely to be expensive than the cost of electricity supply through hybrid mini/grid system [17]. Moreover, the hybrid energy system can prevail over the irregular behavior of renewable energy resources, and improve overall system performance [18] [19]. Our objective of this study is to propose a hybrid mini-grid system for a selected off-grid rural area using the locally available energy resources. The study will investigate and try to give an understanding on the following points to derive if the proposed hybrid mini-grid system can be a potential solution to replicate in rural off-grid areas of Bangladesh or not:

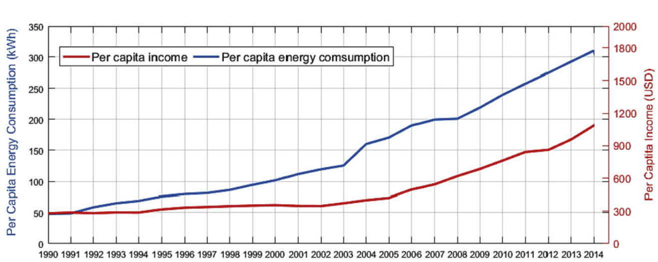

Fig. 1. Per capita energy consumption vs per capita income of Bangladesh [94].

1. To justify the need for deploying renewable energy resources considering the critical overview of power generation situation of Bangladesh
2. To present the status and progress of solar PV and possibility of generating energy from rice-husk feedstock as a biomass resource
3. Justification of installing a hybrid mini-grid by conducting a techno-economic feasibility study
4. To justify the aspect that hybrid mini-grid is superior to diesel-only system in terms of energy costs and environmental pollution
5. To Investigate the behavior of different uncertain components of the hybrid mini-grid on the economic prospect of the system
6. To inspect the variation in selling rate ($/kWh) of electricity and government subsidy on the payback periods
7. To justify the need of a sustainable business model for the proposed hybrid mini-grid and identify its associated challenges

The organization of the rest of the paper is as follows: Section 2 briefly provides an overview of the energy scenario of Bangladesh along with the present status and progress of Solar PV and rice-husk based biomass power generation. Section 3 represents the methodology of this study: a case study is developed, data are gathered and analyzed, hybrid mini-grid network architecture is selected, and its energy management strategies are presented, and finally, system evaluation criteria are discussed. Section 4 represents simulation results and discussion: hybrid mini-grid configuration is selected based on the system evaluation criteria and sensitivity analysis is carried out. Section 5 then denotes the business and financing model with its strategies and associated challenges, while discussion and concluding remarks are described in Section 6.

2. Energy scenario of Bangladesh

Bangladesh has a total installed capacity of 13,299 MW but taking into account the derated capacity, the installed capacity is now 12, 628 MW as of June 2017 of which public and private sector are contributing 52% and 42% respectively [20]. The country recorded a maximum generation of 9,479 MW in June 2017. However, it is burdened with a significant electric power transmission and distribution loss of 10.49% [21].

Energy price has seen several hikes during last four years and increased as much as 120%. At the same time, electricity demand has observed a quick upsurge due to economic progress, speedy urbanization, and industrial development in the country. From 1990 to 2016, the total electricity consumption is increased by 9.1 times; electrifying around 55% of people from 20% during this period. In recent years, both installed capacity and electricity production has increased remarkably, however, the available capacity is regularly insufficient due to decreases in the output and thermal efficiency and failures of power generating units and consequently, the country experiences severe load shedding especially in summer season [22]. Fig. 2 demonstrates power generation condition of Bangladesh for the period from 2006 to 2016. It is evident from Fig. 2 that the maximum power production capacity has increased to around 11,500 MW in 2016 with an average yearly growth of 10% from 4,150 MW in 2006. The yearly installed capacity is significantly higher than the yearly demand excluding only the period from 2008–2010, is also seen in Fig. 2.

Under the new generation planning of BPDB, it is decided to add 13,375 MW to the national grid during the period 2013–2017. Of the planned new generation unit around 2,500 MW by Natural Gas, 1,140 MW by Furnace oil, 112 MW from solar and wind, 225 MW by LNG and 3838 MW will be produced from national and imported

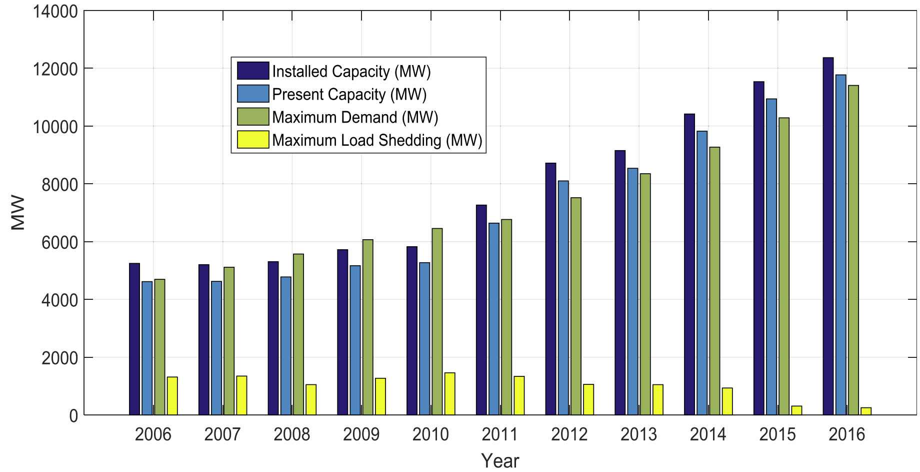

Fig. 2. Electricity supply and demand scenario in Bangladesh [95].

coal [23]. This suggests that the country is heavily relying on coal and gas for its energy supply and this trend of energy supply will continue until 2041 according to Power Sector Master Plan 2016. However, considering the crisis in gas production [9], insufficient domestic coal mining [11], and also having no oil field in Bangladesh [24], leaves the country highly dependent on the national and imported natural gas, imported oil and coal to produce its electricity, and as a result the dependence on imported fossil fuel will rise alarmingly.

Of the power plants already constructed, as yet, only around 30% was completed as scheduled whereas, 70% was built 1–4 years behind schedule. In this circumstance, it is indispensable to capitalize on alternative energy supply possibilities in forthcoming energy plan to electrify the rural areas as grid supply option in those areas is also not financially interesting. Several research studies [24–26] also stressed out on increasing the share of renewable energy as a way out for ongoing and future energy crisis in Bangladesh while achieving the aim to reduce greenhouse gas emissions at least 5% by 2030 committed under the Paris Agreement. The GoB has planned an outline of generating about 3,100 MW, more than 10% share of total energy generation, from renewable energy sources by 2021 as illustrated in Fig. 3. It is seen from the figure that GoB emphasized more on solar based renewable power generation followed by the wind and biomass energy. However, the renewable energy targets of GoB for year 2015 and 2016 were not achieved completely mainly due to the failure of adopting suitable renewable energy policies [27]. To achieve the renewable energy 2021 target, the GoB needs to act promptly now. Our aim of this study is to propose a hybrid mini-grid based power generation system depending on solar PV and rice-husk feedstock as a biomass resource that can help to achieve the renewable energy ambition of GoB. Subsection 2.1 and 2.2 of this section discusses the current status and prospects of Solar PV and rice-husk feedstock as a biomass resource.

2.1. Present status of solar PV

Bangladesh has enormous potential in solar power generation due to plenty of sunshine throughout the year that the country receives. NASA Surface Meteorology and Solar Energy Database reveals that the country obtains daily sun radiation in the range of 4–6.5 kWh/m^2 [28]. In theory, Bangladesh obtains approximately 70 PWh of solar energy each year which is above of 3000 times higher than the total present electricity generation in the country [29].

The GoB has introduced several solar initiatives such as solar irrigation, solar mini/micro-grid, solar park, solar rooftop, solar boating, solar-powered drinking water system etc. The major acting

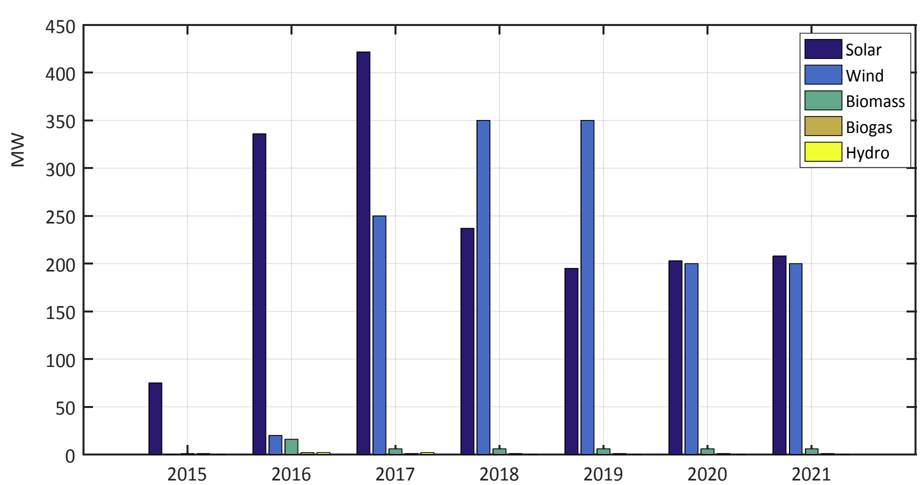

Fig. 3. Year-wise renewable energy installation target [11].

organizations of GoB to bring solar energy to the doorstep of rural people are SREDA (Sustainable and Renewable Energy Development Authority) and IDCOL (Infrastructure Development Company Limited). IDCOL initiated the SHS program in 2003 with an ultimate goal of commercialization and to support and enhance the Government's vision of ensuring ‘Access to Electricity for All’ by 2021 program [30]. On the other hand, SREDA was formed in 2012 as a nodal agency to promote, facilitate and disseminate sustainable energy, dealing both the areas of renewable energy and energy efficiency [31]. IDCOL offers refinancing and grant support as well as required technical support to the 57 Partner Organizations (PO) currently to implement the solar program. Under this program, close to 4.5 million SHSs have already been installed in the un-electrified countryside of Bangladesh till August 2016, with a capacity of above 175 MWp that made the SHS program the largest and most successful worldwide. Fig. 4 displays the growing trend of SHSs in Bangladesh. It is observed from Fig. 4 that the biggest growth came in the fiscal year 2013–14, making the biggest jump of 57% from the previous fiscal year.

Besides SHS program, solar Irrigation pump and rooftop solar has reached installed capacity of above 15 MW in 2016. Although, several large-scale grid-connected solar power projects are currently being constructed, the on-grid Solar PV installation is limited to only 14.95 MWp until 2017. The different form of Solar based power generation capacity is given in the following Table 1.

The GoB has a target to finance further 1500 solar irrigation pumps by 2018 of which 366 are already in operation. Additionally, IDCOL has permitted 26 Solar Mini-Grid Projects, of which 11 are already operating successfully while the rest are under development. The GoB has set a total target of adding 1739.8 MWp of Solar PV consisting of SHS, Solar Irrigation, Solar Mini-grid and so on through several solar installation programs to obligate the renewable energy share to be 10% by 2021 [32].

2.2. Rice-husk as a fuel supply for biomass energy in Bangladesh

Biomass usually refers to rice-husk, crop residue, jute stick, wood, animal waste, municipal waste etc., that are widely used as substitute energy resources in the low-income countries for the purposes of cooking, heating and other essential domestic activities [33]. At present, biomass accounts for 8.5% of the world's total energy consumption which is also the fourth largest source of energy [34]. The economy of Bangladesh is significantly affected by the agricultural sector and almost 65% of country's economic activities are based on agricultural sector [35]. In Bangladesh, the main sources of biomass are agricultural residues (45%), wood and wood wastes (35%) and animal dung (20%). The agricultural residue is one of the key sources of energy for the rural people. The country is very fertile and 59% of the total land is arable where rice is the chief agricultural products. Food and Agricultural Organization (FAO) reported that Bangladesh, 4th largest rice producing nation, has produced 51.8 million tonnes of rice in FY 2014–15 [36]. The country produces roughly 10 million tonnes of rice-husk annually from nearly 50 million tonnes of paddy and of which about 7 million tonnes are being used for rice parboiling, domestic cooking, poultry, and as fish feed etc. [37]. The rest amount is often burnt in open space or thrown away which creates major environmental pollution in the rural vicinity. While rice-husk is one of the major sources of biomass energy in Bangladesh which contributes significantly to rural primary energy consumption, it can also be an effective option for electricity generation. According to the FAO statistics, the amount of paddy production in Bangladesh has shown an increasing trend over the last 20 years, evaluating data from 1993–2013, and will continue to rise in future; a projected rice production increase up to 71 million tonnes in 2030, yielding a growth rate of 2.35% yearly [38] [39]. Fig. 5 illustrates the rice production (in million tonne) trend in Bangladesh.

Hypothetically, about 200 kg of husk can be attained from each tonnes of paddy, however, practically, it was found that the quantity is on average 187 kg of husk [40]. The average caloric value of rice-husk is 14,274 kJ/kg and depending on the technology used 1.5–4 kg/hr rice-husk is required to generate 1 kWh of electricity. A study conducted on the prospects of rice-husk based power generation finds that Bangladesh can generate as high as 7,682 GWh of electricity with a total capacity of 1,066 MW by 2030 using rice-husk [38].

In Bangladesh, tapping the potential of biomass, two rice-husk based power plants are already established; one of 250-kW at Gazipur and another of 400-kW at Thakurgaon. The 250-kW rice-husk gasification power plant established at Kapasia, Gazipur is

Table 1
Present development of different solar based power generation in Bangladesh [27].

SL. No.	Type	Capacity (MW)
1	Solar home system	175
2	Solar irrigation	4
3	Rooftop solar (residential)	11
4	Rooftop solar (Office Building)	2.3
5	Grid-tied Solar	14.95
6	Solar mini-grid	2.19

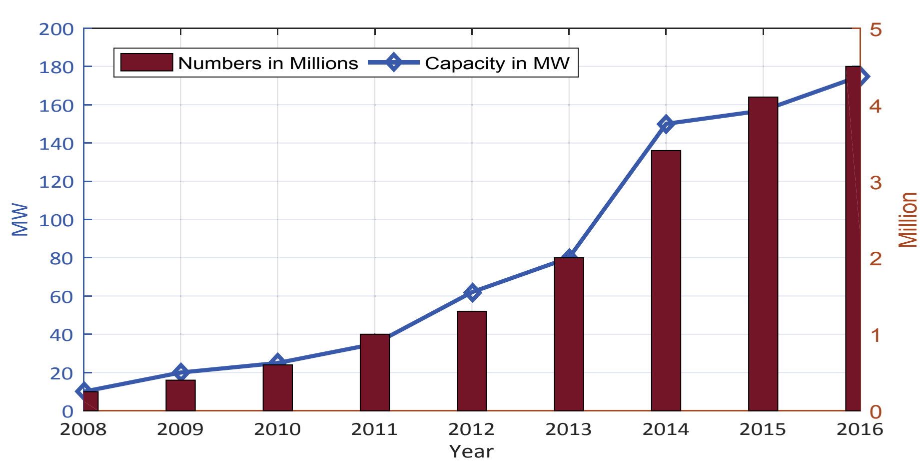

Fig. 4. SHS installation progress of Bangladesh [27].

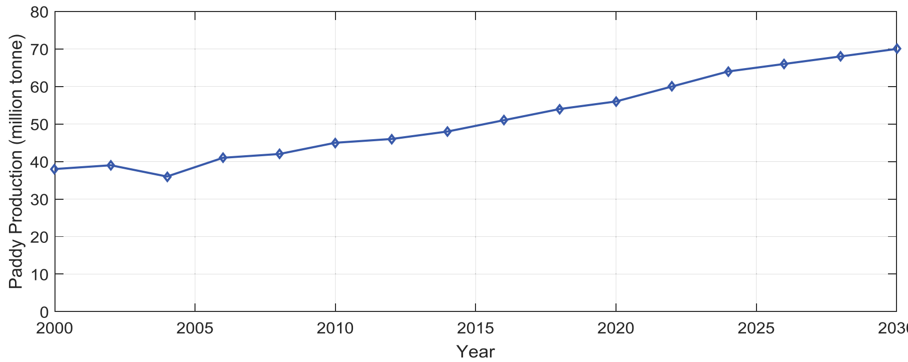

Fig. 5. Increasing trend of paddy production in Bangladesh [38] [39].

the first ever biomass based power plant in Bangladesh which is financed by 60% from World Bank, 20% from IDCOL and 20% from Dreams Power Private Limited (DPPL). The plant consumes rice-husk at a rate of 300 kg/hr. The electricity Production cost of the plant is about 4.3 BDT/kWh ($0.053) after subsidy [41]. On the other hand, IDCOL has solely provided the fund to establish the 400-kW rice-husk based power plant. The total cost of the project is estimated about 64.25 million BDT [42]. The plant needs around 1.6–1.8 kg of rice-husk to produce 1 kWh of electricity.

Due to the huge potential in rice-husk based power generation, GoB has targeted to install biomass based power plants with an aggregate capacity of 47 MW by 2021 to electrify off-grid areas through public-private initiatives. The World Bank is financing these sorts of projects in Bangladesh through the Rural Electrification and Renewable Energy Development Project (RERED). IDCOL, REB and other development agencies are very much keen to replicate these efforts for biomass based power plants and invest in rice-husk based power generation as it is already a successful model for off-grid electrification in many leading rice producing countries like India, Vietnam, Thailand, and China [43–46].

3. Research methodology

Several studies have been done in the area of Hybrid Energy System (HES) for rural electrification in Bangladesh. Most of these studies [47–50] are limited to the techno-economic feasibility of a HES for a given location, but this study delivers a multifaceted analysis combining the technical, economical, commercial and social aspects taking into account the uncertainty in the power sector of Bangladesh. The study initiates providing an overview of Bangladesh's power sector which portray the critical aspects of the sustainable supply system. In this part of this study, the present status and prospects of solar PV and rice-husk as a fuel supply for biomass energy in Bangladesh along with the actions taken for promoting these resources by the GoB and private or social sector entities has been described. Later, a case study is developed, considering two connected un-electrified villages in a low-rate electrified location and their available resources to build a hybrid mini-grid plant to meet their energy needs. In our study, the social assessment reflects how a village is formed, socio-economic condition of the local population, the energy situation of the neighborhood, the energy need of different households, commercial needs such as small shop, battery powered auto-rickshaw charging stations, farming and small industries, community-related needs. The technical aspect efforts to reflect on the various appliances that are used, the load profile, the energy management strategy, and the design and simulation of the combined photovoltaic and biomass plant with battery storage and diesel generator as back-up using a software package, HOMER, developed by National Renewable Energy Laboratory (NREL). The business aspect reflects on proposing and testing a new financing and co-ownership proposition along with the challenges and scopes involved.

3.1. Background of selected area

The selected off-grid rural Villages/Mauzas for this study are located in the north-east of Bangladesh in Saldanga union parishad of Debiganj Upazila under the Panchagarh district in the Rangpur Division. Debiganj Upazila has the lowermost level of electrification rate in the Panchagarh district. The latitude and the longitude of the Saldanga Union are 26°11′51.7″N and 88°41′22.1″E. This area is on the northeast border of West Bengal state of India, and many parts of this area were part of India-Bangladesh enclaves until 2015. There are 10 villages in the union parishad where around 18,222 people are living in about 4,200 households refer to around 420 households per village [51]. The average household size is 4.6. Farming is the main occupation of about 90% of the villagers. Many parts of the villages are not well linked by road and transportation is available in the form of vans, bicycle, rickshaw and battery powered auto-rickshaw. The union is under Polly-Bidyut Samity. Bangladesh Population Census 2001 estimated that 6.10% dwellings had access to electricity at that time. According to the census report 2011, only about 7.8% people have access to electricity from of the Union, in four of the villages it's less than 5%, that made it lowest among the other unions of the Upazila, which presents a prospect for off-grid electrification of the villages in the union [51,52]. This suggests that the growth of electrification in last 10 years was below 2% that makes it one of lowest paced grid electrification region in the whole country. The annual average temperature of the district differs from extreme 30.2 °C to lowest 10.1 °C while the average rainfall of the district stands at 1,955 mm. The type of soil of this area is mostly sandy and alluvial; such as the type of the old Himalayan basin. The nearest town from the selected villages is Debiganj, which is around 20 km away. The surface area around the village is plain. The village has no supply water facilities but in the arrangement of water-wells and hand pumps. The local population of non-electrified areas depend on kerosene and candles for lighting and fuel-wood, agricultural residues and cow-dung for cooking purposes.

At an initial level, two of the less un-electrified villages (Debottar Saldanga and Amarkhan) are chosen to set up the hybrid power plant and later depending on the obtainability and availability of rice-husk and the capacity of the plant, the nearby villages could be connected to the network if economic of scales is found suitable. The location of the villages is displayed in Fig. 6; marked with the red circle. These two villages have an average

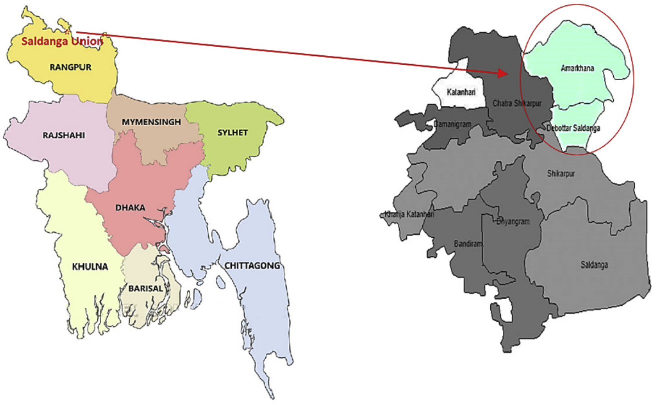

Fig. 6. Selected region for installing Hybrid mini-grid.

electrification rate of just 3.9%. The detail statistics of the studied area are given in the following Table 2.

3.2. Assessment of energy resources

3.2.1. Solar energy resource

The solar irradiation of the studied area was taken from NASA Surface Meteorology and Solar Energy Database [28]. The average monthly solar radiation level in the study area is 4.85 kW h per square meter per day (kWh/m^2/day). The total solar energy potential of the study area is estimated as 1,770 kWh/m^2/yr. The monthly radiation, the cleanliness index and temperature data of the study area are shown in Table 3.

Table 2
Details of the selected region to implement Hybrid mini-grid [51,52,96].

Particulars	Details
Name of the Mauzas/Villages	Debottar Saldanga and Amarkhana
Upazila, District	Debiganj, Panchagarh
Country	Bangladesh
Latitude and Longitude	26°11′51.7″N, 88°41′22.1″E
Climate and Weather Specifics	hot, wet, humid and Tropical Dry, Average Temperature- 25 °C
Area of the Union	964 Acres
Total Population	2792
Irrigated area	502 Acres
Major Crops	Paddy, jute, wheat, Potato, onion, ginger, turmeric, Chinese almond
Rivers available	1
Grid electricity	3.9%
Total Households	607
Profession	Agriculture-86%, non-agricultural laborer- 3%, Business-6%, Service- 2%, Other −3%
Literacy Rate	36%
Education facilities	2
Average Income per household	$ 95/month

From Table 3, it is comprehensible that the solar radiation for the selected villages is available practically throughout the year. The radiation level rises between March and May and lessens during the rainy season from July to September. Depending on the solar radiation obtainable on the tilted surface, the hourly energy production of the solar module is estimated by the subsequent equation in HOMER,

$$E_{PV} = C_{PV} D_{PV} \left(\frac{H_T}{H_{T,STC}} \right) \left[1 + \gamma_P \left(T_C - T_{C,STC} \right) \right] \tag{1}$$

where, E_{PV} is the Energy generated by PV array (kWh), C_{PV} denotes the rated capacity of the PV array (kW), D_{PV} represents the PV derating factor (%), H_T characterizes as the solar radiation incident on the PV array in the current time step (kW/m^2), $H_{T,\ STC}$ characterizes as the incident radiation at standard test conditions (1 kW/m^2), γ_P is the temperature coefficient of power [%/°C], T_C is the PV cell temperature in the current time step [°C] and $T_{C,\ STC}$ is the PV cell temperature under standard test conditions [25 °C]. Derating factor accounts for losses such as soiling of the panels, wiring losses and losses due to shading, snow cover, aging etc. and it ranges in between 0.5 and 0.95. The study considers monocrystalline-based solar panels with an efficiency of 16% to be used in the proposed hybrid mini-grid system. The lifetime of the selected PV arrays for this project is taken as 25 years and monthly adjustment type horizontal axis tracking system is considered the PV system. Derating factor of PV and ground reflectance (radiation that is incident upon the PV modules) are assumed to be 80% and 20%. Surfaces with higher ground reflectance values reflect more light than surfaces with lower ground reflectance values. Ideally, PV modules should be installed in high ground reflectance areas as this can increase the output power considerably [53]. A range of 0–200 kW PV sizes are considered for optimization purpose.

3.2.2. Biomass energy resource

The main crop of Debiganj Upazila is rice and wheat. Other than that jute, potato, sugarcane, tea, onion, ginger, turmeric, Chinese almond and different fruits & vegetables are grown. The cropping intensity of the Panchagarh district is one of the highest of the country which is about 188%. The total irrigation area covered under the Debiganj Upazila is almost 34,225 acres producing about 393,506.8 tonnes of rice. The rice production of Debiganj Upazila is second highest in Panchagarh district after Boda Upazila. There are

Table 3
Daily solar irradiation, clearness index and average temperature of the selected area [28].

Month	Daily radiation (kWh/m^2/day)	Clearness Index	Average minimum temperature (^{0}C)	Average maximum temperature (^{0}C)	Average mean temperature (^{0}C)
January	4.13	0.75	6.27	25.2	15.74
February	4.99	0.75	8.69	29.4	19.50
March	5.89	0.75	12.8	34.7	23.75
April	6.27	0.75	16	33.4	24.70
May	6.00	0.73	18.5	30.6	24.55
June	4.97	0.72	20.6	29.5	25.05
July	4.21	0.70	20.8	28.6	24.70
August	4.26	0.68	20.6	28.9	24.75
September	4.01	0.68	19.3	28.1	23.70
October	4.80	0.71	15.2	27.3	21.25
November	4.61	0.73	10.2	26.1	18.15
December	4.09	0.74	7.35	25.1	16.23

Table 4
Rice-husk production in the selected Upazila.

Rice production (tonnes)	Residue used	Processed by mill (70% of total) (tonnes)	Residue Product ratio	Residue (tonnes)
105,131	Rice-husk	73,591.7	0.22	16,190.2

total 307 rice mills situated in Panchagarh district among which 84 are located in the Debiganj Upazila [54]. None of the rice mill is automated in operation and uses traditional and inefficient parboiling method. The parboiling in small mills is done with primitive equipment and a majority of furnaces operate at low levels of efficiency (around 20%). This leads to considerable wastage of the bran and husk mixture [55].

The main two type of rice (Aman and Boro) sums up to around 105,131 tonnes of paddy production per year in Debiganj Upazila [54]. 30% paddies are processed by the farmers themselves with the help of old rural technology and rest 70% are processed at rice mills [56]. Hence, the amount of rice-husk to be obtained from rice mills alone from Debiganj Upazila is around 16,190.2 tonnes per year considering the Residue Product Ratio (RPR); as presented in Table 4.

In our analysis, the maximum collection capacity of rice-husk is considered around 20% (9 tonnes/day) of the total rice-husk available in the Upazila. Consideration of maximum collection capacity will ensure that the supply of rice-husk is not affected in the power plant in future if lower rice production is experienced in some years in the Upazila. Also, the supply of husks from rice mills throughout the year is not uniform in quantity. Estimates show that rice-husk supply is surplus for approximately nine months around the year depending on the production type of paddy in a particular area. The main two crops [Aman (October–December) and Boro (March–May)] of Debiganj Upazila are available for 6 months of the year. Thus, leftover husk can be stockpiled for the usage to overcome the shortage of rice-husk for the remaining months of the year. The rice-husk will be collected mainly from the rice mills and if any individual household expresses their interest in providing husk then that too will be collected. The rice mills are mostly clustered in different zones of the Upazila. The project will consider low cost automatic battery driven rickshaw vans in a capacity that to collect the rice-husk from every part of the Debiganj Upazila to the power plant premises. Furthermore, low cost husk storage will be constructed in the vicinity of the power plant to store the collected husk temporarily and ensure a continuous supply.

The maximum annual output electricity (kWh) of a biomass gasifier can be computed as [57],

$$E_{BM} = P_{BM} * CUF * [365 * (\text{Operating hours/Day})] \tag{2}$$

where, P_{BM} is the maximum rating of biomass gasifier system and CUF is the capacity utilization factor, taken as 0.25 in our study. The maximum rating of biomass gasifier (kW) based on the available rice-husk can be calculated by the following equations [58]:

$$P_{BM} = BM_{TA} * 1000 * CV_{BM} * \eta_{BMG} \tag{3}$$

where, BM_{TA} is the available rice-husk (tonnes/year); η_{BMG} is overall energy conversion efficiency of biomass generator (%); CV_{BM} is calorific value of biomass (KJ/kg). Biomass Generators (BG) minimum load ratio is taken as 0.3. Considering the maximum cap of rice-husk collection (9 tonnes/day), a range of BG sizes are considered for optimization purpose in between 0 and 65 kW.

3.3. Estimation of electric load demand

The electricity demand of rural areas in the country is extremely low compared to the urban areas. The estimated number of households in the selected villages are 607. Normally, a rural household uses 3 to 5 LED bulbs for lighting, one or two cooling fans and a television for entertainment purpose. The authors could not collect the exact load profile of the selected area as the studied area is off-grid. Under this circumstances, the load estimation for this rural area was constructed based on a number of studies on similar rural areas within the country [59–62] as well as in southeast Asia

Table 5
Estimated load demand of the selected villages.

SL. No.	Load type	No.	Power (W)	Summer (Apr–Oct)		Winter (Nov–Mar)	
				h/day	**W-h/day**	**h/day**	**W-h/day**
1	**Domestic**						
	Low-energy CFL Bulbs	3	10	6	180	7	210
	Television	1	30	5	150	6	150
	Refrigerator[a]	1	50	24	1200	20	900
	Ceiling fans	2	20	12	480	0	0
	Mobile Charger	2	5	3	30	4	40
	Total				1920		1300
	No of houses	607			640,560		351,700
2	**Industrial/Commercial/Community**						
	Shops	20	400	10	80,000	8	64,000
	Street Lights	10	20	8	1600	10	2000
	School	2	400	8	6400	8	6400
	Hospital	1	500	24	12,000	24	12,000
	Post Office	2	120	8	1920	8	1920
	Rice-Mill	2	20,000	8	320,000	6	240,000
	Small Industry	4	2000	12	96,000	10	80,000
	Battery Charging Station	2	5000	15	150,000	15	150,000
	Total				1,308,480		908,020
3	**Agriculture**						
	Irrigation Pump	10	1500	6	90,000	3	45,000
	Water Pump	2	750	6	9000	4	6000
	Total				99,000		51,000

[a] Assuming 20% Village households has Refrigerator.

[63–66]. The total demand estimated considering the rating and requirement of appliances for various energy consumption sectors are specified in Table 5.

The rice mills in the rural areas are mostly small to medium sized. A typical medium size rice mill of the selected area consumes around 320 kWh/day with a peak demand of nearly 20 kW. These mills mostly function a single shift of 6–8 h throughout the year. The study assumes that the rice mills operate during the daytime when the domestic demand is too low. It is noteworthy that the battery charged auto-rickshaws and easy-bikes are getting intensive popularity in the rural areas resulting extra demand for battery charging station and therefore, this sort of load is also considered in the electricity load model of the selected area. An easy-bike, having a set of five batteries with a voltage level of 60 V, consume on average 1-5 kWh of electricity day-to-day and require 4–5 h to be completely charged suggests for a total number of 20–30 bikes in these 2 villages need 2 battery charging station each of 5 kW capacity. The load profile has been created keeping in mind the seasonal demand. HOMER generates hourly load values from the scaled-load data based on the monthly averaged daily load profiles. To make the load profile more realistic, we applied daily 10% and hourly 5% randomness noise input to it; although increasing randomness results in higher peak load. The load has been categorized into two different categories, as described below:

- The essential load is the electrical load that requires to meet immediately in order to avoid unmet load [67]. In our study, domestic load and industrial/commercial/community load are considered as an essential load. The peak primary load is estimated as 110.61 kW in our system. The primary load demand is estimated as 1,108.25 kWh/day. An hourly load profile has been designed for essential load in HOMER for both summer and winter season is shown in Fig. 7. Load factor for the primary load is estimated as 0.42.

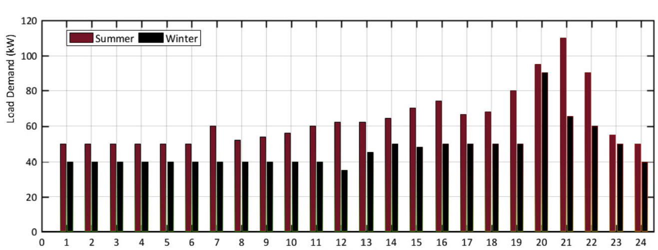

Fig. 7. Load profile of the studied area.

- Deferrable load, includes agriculture load and battery charging stations in our study, is defined as the electrical demand that can be satisfied any time within a well-defined time window. If the power supply ever surpasses the primary load, the excess energy can serve the deferrable load [68]. The peak is assumed as 10 kW for deferrable load in our system. The deferrable load demand is approximately 75 kWh/day.

3.4. Hybrid mini-grid network system

Hybrid systems are designed by the hybrid interconnection of several units such as AC and DC energy sources, energy storage units, AC and DC loads, AC/DC, DC/DC, or DC/AC [69,104]. A hybrid coupled (DC-AC) bus system architecture designed to provide AC electricity supply for the planned hybrid mini-grid is shown in Fig. 8.

The Diesel Generator (DG) and Battery Energy System (BESS) can be used as backup due to the intermittent nature of PV and unreliable supply of rice-husk all year around. The incorporation of BESS is needed to offer short-term power balancing and/or long-term energy management as well. Acting as a bridge between the DC and AC side, the bi-directional inverter can convert DC from the PV panels or battery to AC to supply the loads and can also accept any extra energy from AC sources to recharge the battery, which optimize the energy flow in the system and reduce losses [70,105]. A system with multiple generators that can be dispatched according to the level of demand can bring the battery size to the lowest level for bridging between PV and generator operation [17]. Also, during low load requirements, the fuel consumption is higher compared to the electricity that is generated, thus it is recommended not to run the generator at a lower load than 40% of DG's rated capacity [71] justifies the incorporation of multiple size generators in the system. But multiple DGs lead to the surge of the initial investment cost and thus, to supply cheap energy, this aspect of incorporating multiple diesel generators is not considered in our designed system. The major advantage of this hybrid coupled system is that if the DC-AC inverter is out of order for some reason, only the energy supply from PV and Battery will be interrupted but the load demand can still be met with the reserve capacity from DG and biomass sources.

3.5. System economics

Economic data includes capital cost, replacement cost, Operational and Maintenance (O&M) cost of system components. Land cost and the labor installation cost of every equipment's is

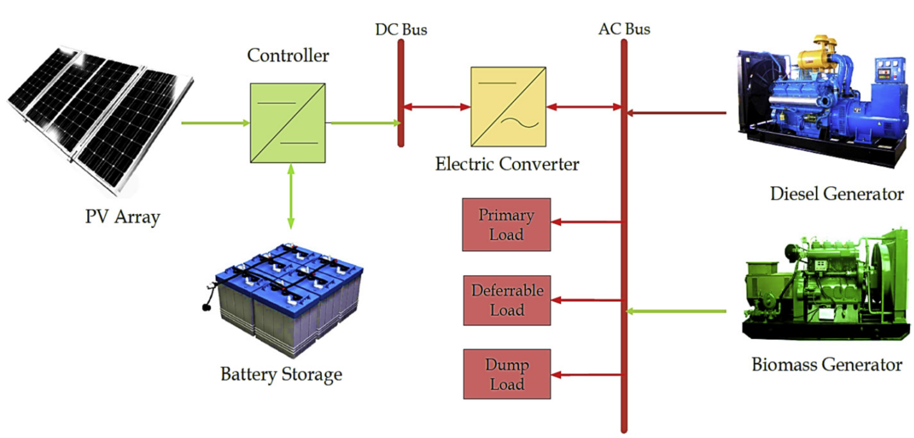

Fig. 8. Proposed Hybrid mini-grid system.

considered into the systems fixed capital cost. HOMER does not consider the cost of distribution network separately, therefore, an approximated capital and O&M costs of distribution network for 607 households were also considered in the systems fixed capital cost. The cost of biomass is taken as $ 30/tonnes [72], the cost of diesel at present rate in Bangladesh is $ 0.86/l, the annual discount rate is 6% and a project life of 25 years are considered during the simulation of the planned Hybrid mini-grid system. The cost curve is linear means when size increases cost also increases for most of the components in the Hybrid mini-grid system. This effect is considered while estimating the costs of system components. The land acquiring is a critical factor when we consider an electricity generation plant in a densely-populated country like Bangladesh. Khan et al. (2015) reported that the area requirement for 100 kW solar PV is 0.61 acre in Bangladesh, though this requirement substantially varies according to the PV module efficiency [73]. It is sometimes challenging to acquire the land as most of the people of rural villages have limited lands and in most cases, these small lands are their only means of earning by farming. It can be anticipated that not many will be interested in selling their land unless they see a clear benefit. Table 6 represents the cost details of the proposed Hybrid mini-grid system.

3.6. System operating strategy

In a hybrid coupled AC-DC system, control strategies and power management schemes are the most important characteristics in accomplishing the maximum system reliability and operational efficiency [74]. The control system guarantees the balancing between generation and load to ensure the smooth running of the system. Usually, the control arrangement of hybrid energy systems can be categorized into three groups; centralized, distributed, and hybrid control. Each energy source of the hybrid energy system is supposed to have its own controller which can regulate optimal operation of the corresponding unit based on real-time information. In our proposed hybrid mini-grid system, centralized control architecture is assumed to be used. In this control system, the measurement signals from all of the local controllers of all the energy are united in a group and then, sent to a centralized controller [75]. The centralized controller behaves as an energy supervisor and makes decisions and perform any control operation based on all measured signals and a set of pre-programmed constraints and objectives [76]. The adapted power management strategies based on centralized control architecture for the proposed hybrid mini-grid system is described below:

- During usual operation, the renewable energy resources such as PV, Biomass along with battery will attend the load. Once the generation by PV and Biomass surpasses the demand, the battery consumes energy and becomes charged. If the State of Charge (SOC) of the battery is higher than the maximum limit, the surplus power will be delivered to deferrable load and then to dump load to avoid overcharging of battery. While discharging battery, if the SOC falls below its allowed lower limit of 20%, the BESS must be detached from load to avoid battery over discharging. At this point, the offline DG generator starts to supply the load demand provided that renewable energy resources can't meet the load demand.
- During peak load demand period, if the renewable sources cannot serve the demand adequately, the DG generator starts automatically and provides the needed partial demand. At this time, DG generator starts operating at full rated power and the extra power after fulfilling the load demand is used to charge BESS. This strategy is called cycle charging strategy [77].

3.7. System evaluation criteria

The total Net Present Cost (TNPC) is used to characterize the life-cycle cost of a system in HOMER. The TNPC consists of initial set-up costs, replacement, operations & maintenance and fuel costs in addition to the cost of purchasing power from the power grid, if any, and other costs for instance penalties for greenhouse gas emissions. The following equation is used in HOMER to estimate TNPC [78]:

$$\mathrm{TNPC} = \frac{C_{TA}}{\mathrm{CRF}} \tag{4}$$

where C_{TA} is the total annualized cost ($/yr) and CRF is capital recovery factor (CRF) is estimated by the following equation [78]:

$$\mathrm{CRF} = \frac{i(1+i)^N}{i(1+i)^N - 1} \tag{5}$$

where ‘i’ is the annual interest rate (%) and N is the project lifetime (years)

The cost of energy produced (COE) is the average cost per unit (kWh) of useful energy generated by the supply option. It can be expressed as:

$$\mathrm{COE} = \frac{C_{Ann}}{E_{Total}} \tag{6}$$

where E_{Total} is the total electrical load served in kWh/yr, C_{Ann} is the Total annual cost in $/yr.

In this analysis, the financial assessment is also determined by the payback period, which is calculated using the following Equation [79].

$$\text{Payback Period (PP)} = \frac{I}{R - E} \tag{7}$$

where I is the investment, R is the return, and E is the expenses.

Table 6
Economic inputs for configuring Hybrid mini-grid.

Equipment	Capital cost	Replacement cost	O&M cost	Lifetime	Source
PV Module[a]	$* 1300 kW^{-1}	$ 1300 kW^{-1}	$ 1 kW^{-1}	25 yr	[97]
Converter	$ 150 kW^{-1}	$ 150 kW^{-1}	–	15 yr	[98]
Battery	$ 300 kWh-1	$ 300 kWh-1	$ 0.01 kWh^{-1}	15 yr	[64]
Biomass gasifier system	$ 1100 kW^{-1}	$ 1000 kW^{-1}	$ 300 kW^{-1}	20,000 h	[99]
Diesel Generator	$ 700 kW^{-1}	$ 700 kW^{-1}	$ 0.05 kW^{-1}	20,000 h	[86]
Distribution Network	$ 7800 km^{-1}	–	$ 500 km^{-1}	–	[100]
Land Cost[b]	$ 150 kW^{-1}	–	–	–	–

*All the costs are estimated in USD in this paper.
[a] Shipping, handling and Tax.
[b] Personal Communication.

The TNPC, COE and PP as developed above will be used in this research work as main selection criteria of the different feasible supply options.

3.8. Simulation method in HOMER

The simulation method of HOMER follows mainly three key tasks. Firstly, it checks whether the system is feasible. A system is considered feasible if it can sufficiently satisfy the electric loads considering any restrictions imposed. At this stage, HOMER perform an hourly time series simulation for the whole period of one year, computing the presented renewable power, comparing it to the electric load, and determining the action of doing what with additional renewable power in times of surplus, or how best to produce extra power in times of shortage [77]. It also determines the life-cycle cost of the system at this stage.

As a second objective, it finds the optimal value of the input variables over which the system designer has control such as the combination of components and the size or quantity of each. In this optimization process, HOMER simulates various system configurations under user-specified constraint, rejects the infeasible ones, ranks the feasible ones according to TNPC, and represents the lowest TNPC system as the optimal system configuration [78]. Finally, In the sensitivity analysis process, HOMER simulates several optimizations under a range of input variables to measure the effects of uncertainty or changes in the system. Fig. 9 demonstrates the relationship between simulation, optimization, and sensitivity analysis. The optimization oval encircles the simulation oval to characterize the factor that a single optimization includes multiple simulations. Likewise, the sensitivity analysis oval encloses the optimization oval because a single sensitivity analysis consists of multiple optimizations [77].

HOMER has adopted two optimization algorithms. The grid search algorithm (e.g. used for BG and DG) simulates all of the feasible system configurations defined by the Search Space. The default HOMER Optimizer (e.g. used for PV array, battery and converter) uses a proprietary derivative-free algorithm to search for the least-costly system [80]. Table 7 shows both the search space and HOMER Optimizer parameters that has been used for different components considered in designing the proposed hybrid mini-grid system. HOMER will perform hundreds of simulations with different combination of these defined input parameters of Table 7, and then determine the optimal system size of different components which will result in lower TNPC. The optimal sizing parameters may produce some excess electricity in some cases. Excess electricity occurs either by a renewable energy source or by the diesel generator when its minimum output surpasses the demand and the energy storage system is incapable to absorb it all. HOMER is mainly used in the feasibility studies of energy system modelling and it cannot simulate electrical transients or other dynamic effects.

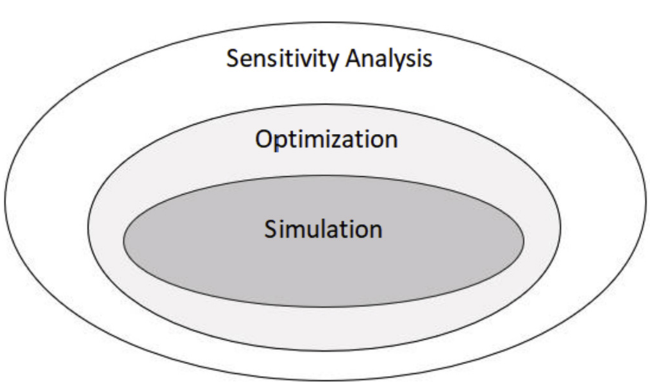

Fig. 9. Relationship between simulation, optimization and sensitivity analysis in HOMER [77].

Table 7
Search space and HOMER Optimizer parameters of different component size.

PV array (kW)	Biomass generator (kW)	Diesel generator (kW)	Battery (kWh)	Converter (kW)
0–200	0	0	0–400	0–150
	30	20		
	40	30		
	45	35		
	50	40		
	55	45		
	60	50		
	65			

4. Simulation results and discussion

Three configurations are considered for the proposed Hybrid mini-grid system depending on the availability of local power generation resources. After investigating each design, HOMER chooses the optimized system for each configuration that satisfies the load demand with the imposed system restrictions. The simulation results for the various Hybrid mini-grid systems are listed in Table 8.

From the simulation results, the Optimal combination for our study is Hybrid mini-grid Configuration-C, in terms of lower per unit energy cost and total net present value. The configuration consists of 103 kW Photovoltaic Panel, 60 kW Biomass generator, 40 kW Diesel generator, 60 kWh Li-ion Battery and 77.2 kW system converter with the cycle charging dispatch strategy. The optimal system parameters obtained from HOMER simulation for Configuration-C can be seen in Annex A.

The annual electricity production for Configuration-C to meet the load demand is 431,932 kWh/yr. Around 38.3% (196,369 kWh/yr) of the electricity demand is met from Photovoltaic plant, while 7.1% (33,651 kWh/yr) and 54.6% (260,236 kWh/yr) of the energy need is supplied from the diesel generator and biomass generator respectively. Hours of operation of PV, BG and DG are 4378 h/yr, 6666 h/yr and 1267 h/yr respectively. Fig. 10 displays the average fuel consumption intensity by DG and BG throughout the year of Configuration-C. Fig. 11 portrays the average monthly electricty distribution by the optimized system of configuration-C. Renewable energy share of this configuration stands at 92.9%. The configuration has negligible unmet load and capacity shortage, but it has around 7% excess electricity production. This excess electrical production cannot be minimized further with lowered generating capacity due to the fact it can affect the reliability of the system. One strategy for reducing excess energy could be increasing BESS capacity but this could be financially intensive due to higher battery storage costs and conversion costs. It is interestingly noticeable that having no BESS in Configuration-B produces significant amount of excess electricity which is over 10% of total produced electricity.

In Fig. 12, the cost breakdown of all the configurations is displayed. The total net present cost of the Configuration-C is around $1.28 M, the operating cost is $58,987, and the initial capital cost is found to be $406,692. The biomass generator costs around 54% of the total net present cost of the system whereas share of cost for both the PV plant and diesel generator stands at only 46%. Per unit cost of energy for the selected configuration estimated as $ 0.188/kWh which is almost 3 times higher than residential consumers tariff ($0.065/kWh) in Bangladesh. This is far from matching the

Table 8
Comparative analysis of Hybrid mini-grid Configurations from simulation.

SL. No.	Description		Configuration-A	Configuration-B	Configuration-C
			PV/Biomass/BESS	PV/Biomass/DG	PV/Biomass/BESS/DG
1	System Sizing	PV (kW)	111	106	103
		Biomass (kW)	65	55	60
		Diesel Generator (kW)	–	40	40
		Battery (kWh)	290	–	60
		System Converter (kW)	124	78.6	77.2
2	Electricity Production (kWh/yr)	Total Electricity	492,428	484,693	476,231
		PV Production	196,369	188,651	182,344
		Biomass Production	296,059	246,700	260,236
		DG Production	–	49,343	33,651
		AC Primary Load	404,437	404,511	404,511
		Defferable Load	27,393	27,427	27,421
		Unmet Load	225	807	0
		Capacity Shortage	428	3483	0
		Excess Electricity	37,190	46,330	34,318
3	Economics	Net Present Cost ($)	1,383,410	1,425,280	1,275,888
		Cost of Energy ($/kWh)	0.203	0.21	0.188
		Initial Capital Cost ($)	415,266	411,619	406,692
		Operating Cost ($)	61,460	64,350	58,987
4	Emissions (Kg/year)	CO_2	Nearly Zero	52,432	31, 054
		CO	228	337	259
		Unburned Hydrocarbons	–	14.5	8.23
		SO_2	103	197	162
		NO_2	811	1,893	1,487
		TSP (Dust)	28.95	34.76	31.64
5	Fuel Consumption	Biomass (tonnes)	592.1	493.4	520.5
		Diesel	–	19,596	12,467
6	Battery Performance	Energy In (kWh/yr)	49,485	–	8,331
		Energy Out (kWh/yr)	39,594	–	6,667
7	Life Expectancy (yr)	Diesel Generator		6.61	11.8
		Biomass Generator	2.61	2.04	2.25
		Battery	5.24	–	6.44
8	Renewable Fraction (%)		100	89.8	92.9

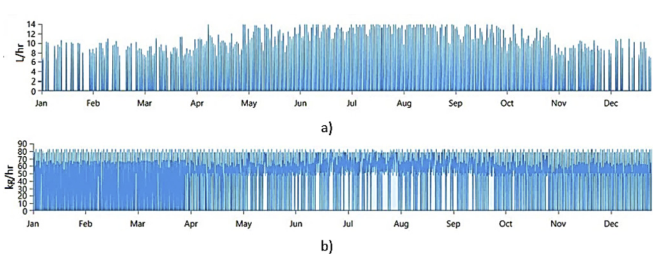

Fig. 10. Fuel summary of a) DG and b) BG of Configuration-C.

grid parity as the government is paying a huge subsidy for electricity generation from conventional power plants. A SHS or diesel based power generation system in this circumstance is more appropriate for reference economic comparison to the Hybrid configuration. SHS operating in the off-grid areas in Bangladesh

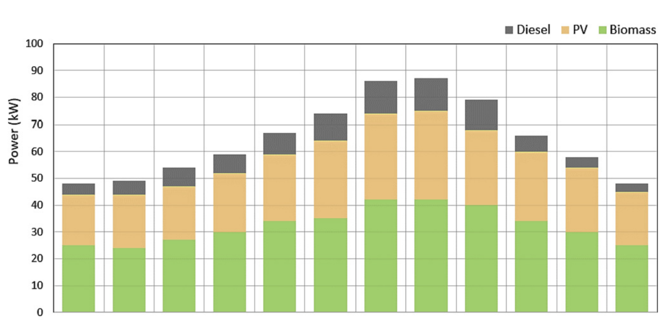

Fig. 11. Monthly distribution of the electricity produced by Configuration-C.

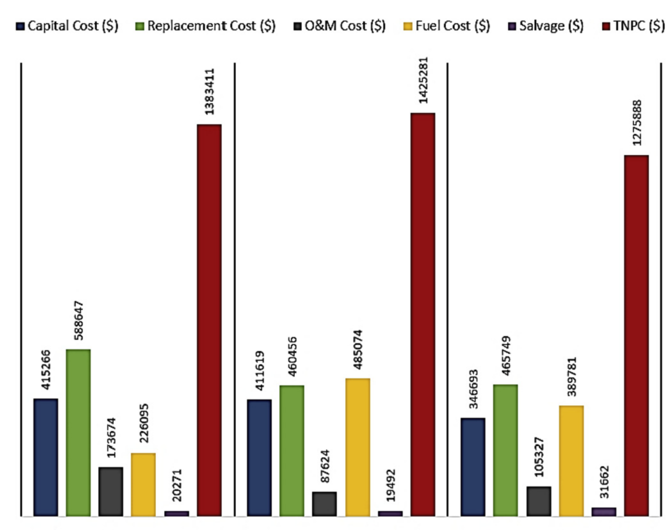

Fig. 12. Cost summary of different configurations.

costs approximately $0.72/kWh which is more than double compared to the diesel-based ($0.36/kWh) mini-grid system [17].

The emission factors for Biomass in our configurations are estimated from the practical emission case of the Roi Et Green Project in Thailand which is a pilot biomass plant project with a capacity of 9.8 MW using rice-husk as the feedstock [81]. It is found that CO_2 emission among all the pollutant components is significantly higher in the diesel generator connected configurations whereas Configuration-A is completely free from CO_2 emission as the purely based on renewable energy. However, Configuration-A is not yet fully emission free as it has other pollutant components shown in Table 8. In biomass-based energy generation, CO emission is to some extent higher than conventional power production, but this can be improved upon refining the combustion efficiency of the biomass power generating unit. Besides, the by-products of biomass gasification are tar, and ash/char. Char is a solid residue that is composed primarily of carbon and also contains ash. In the proposed hybrid mini-grid system, the produced char can be used to make activated carbon and precipitated silica. Activated carbon obtained by the plant can be used in wastewater treatment as an adsorbent to remove organics. Precipitated silica is used as an essential element in the cement industry [82]. The tar can be used in making aromatic polymers, such as plastics and fibers but with the gasification technology it is not encouraged as gasification destroys many of the aromatic rings in the biomass [83]. Therefore, in the proposed system tar will be removed. The char bed filter can also be used as an effective low-cost tar removal solution [84].

From the results of Table 8, one can argue that Configuration-A sharing almost equal per unit cost of energy as Configuration-C and being completely free from primary greenhouse gas emission is the most suitable Hybrid mini-grid configuration for supplying energy. However, as our primary objective is generating cheapest energy for low-income rural areas people while also considering reduced environmental effects, Configuration-C fulfils the primary objective with minimal environmental hazards. Configuration-C saves around $129,579 with lowest per unit electricity cost during the complete life duration of the project than Configuration-A.

In our analysis, we also provide a comparison to the Configuration-C on the ground of environmental benefits based on the present kerosene consumption of off-grid people as most of the rural-households uses either kerosene, or diesel based power generations. Assuming 5 h of daily kerosene uses with a rate of 0.045 l/h, it is found the total burnt Kerosene by the 607 households is 49,850 L per year in the studied area. Reported in the research studies [85], that kerosene emits 2.5 kg/l of CO_2 which equates to 124,625 kg CO_2 emission annually in the studied area. CO_2 emission for Grid supplied energy and diesel based energy generation is estimated based on the electricity need of 431,932 kWh/yr of Configuration-C. It is observed from Table 9 that the proposed Configuration-C reduces the CO_2 emission of around 89% than the grid supplied energy, and 91% compared to diesel based energy generation system. It is also found that the proposed hybrid mini-grid system would produce about 75% lower CO_2 than the existing methods of fulfilling energy needs.

It is also worth to mention that in order to optimize the dispatch strategy of the system; the optimal configuration is run under both the load-following and cycle charging control strategy of HOMER. It is found that load following dispatch strategy increases the cost of energy from $0.188 to 0.189 $/kWh of the system whereas it is more economical under cycle charging strategy saving above of $12,450 during the project lifetime. This is due to the fact that under the cycle charging strategy whenever a generator requires to run to serve the necessity load, it functions at full output power and the excess energy serves the deferrable load and charge BESS.

The simulation results suggest that in terms of reliability, quality, the cost of Energy, emission reduction, and the site location which is far from national grid connection, Hybrid mini-grid Configuration-C is the best-suited optimal solution to implement in the rural study area.

Table 9
Comparative CO2 Emission to supply Energy in the studied system.

Sl. No.	Scenarios	CO2 emission (kg/yr)	Source
1	Configuration-C	31, 054	
2	Grid Supplied Energy	275,140	[101]
3	Diesel based Energy generation	354,616	[102]
4	Kerosene	124,625	[85]

4.1. Comparison to diesel-only system

In our study, the analysis is further investigated, comparing optimal Configuration-C with diesel-only supply system, by economically based on the payback period as an index of monetary benefits. The total NPC for Hybrid mini-grid Configuration-C is found $1.28 M over a period of 25 years. If the total electric load of the studied area is satisfied by diesel-only generator system, then the system incurs a total net present cost of $1.64 M over the project lifetime. Considering the diesel-only supply system as base system and optimal hybrid mini-grid system as the current system gives us a discounted payback period of 6 years. This proves that the Hybrid mini-grid Configuration-C is not only superior in terms of environmental viewpoint but also from economic perspectives. Fig. 13 depicts the cumulative cash flows over the period of 25 years for the base system and current system and the corresponding cross-section between the two systems which provides us the discounted payback period.

4.2. Sensitivity analysis

Sensitivity Analysis helps to study the systems behavior under the uncertainty of different parameters of the optimal system. In the sensitivity analysis, the impact of price variability in Biomass price, diesel price, discount rate, and increased primary load on the cost of per unit energy and total net present cost were observed for Configuration-C. The study also finds diverse payback period for different electricity selling rate to the consumers. Table 10 lists the sensitivity ranges for various input variables.

4.2.1. Sensitivity to the biomass price on COE and TNPC

The price of rice-husk has been varied from $30/tonne to $60/

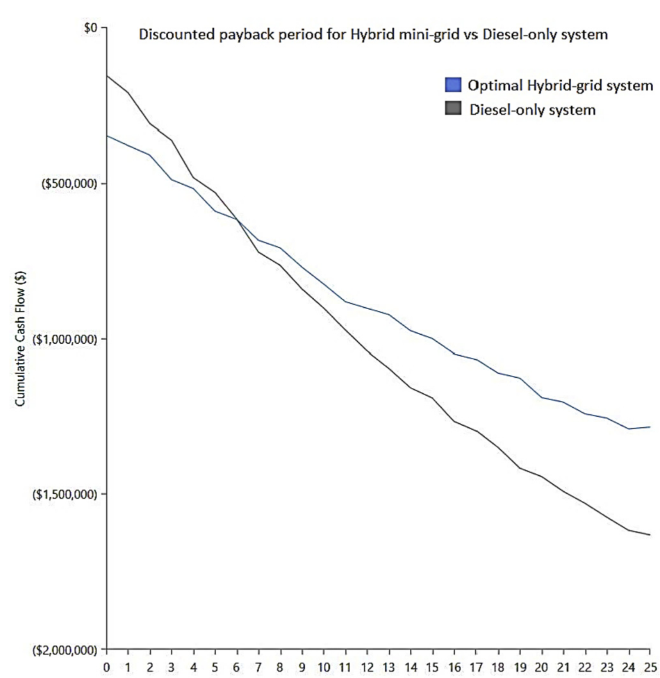

Fig. 13. Discounted payback period of Configuration-C compared to Diesel-only system.

Table 10
Parameter ranges for sensitivity analysis of the Optimal System.

Input Variables	Unit	Sensitivity ranges
Biomass Price	$/tonnes	30[a], 35, 40, 50, 55, 60
Diesel Price	$/L	0.75, 0.85[a], 0.95, 1.1, 1.2, 1.3
Discount Rate	%	2, 4, 6[a], 8, 10
Increment to Primary Load	%	5%, 10%, 15%, 20%, 25%, 30%
Selling Electricity Price	$/kWh	0.3, 0.35, 0.4, 0.45, 0.5

[a] Reference Input.

tonne and COE and TNPC have been assessed accordingly. With the price variation of rick husk from $ 30/tonne to $ 60/tonne, LCOE of the optimal configuration-C varies from 0.188 $/kWh to 0.219 $/kWh. The consequence of rick husk price variation on LCOE and TNPC is demonstrated in Fig. 14.

4.2.2. Sensitivity to the diesel price on COE and TNPC

Diesel price of the Hybrid mini-grid configuration has been changed 0.75 $/L to 1.3 $/L, and its consequence on COE and TNPC has been examined accordingly. It has been observed that both COE and TNPC rise significantly with the increasing price of diesel. The effect of diesel price variation on COE and TNPC is shown in Fig. 15.

4.2.3. Sensitivity to discount rate on COE and TNPC

The discount rate is varied from 2-10% and applied to the COE and TNPC. Lower discount rate yields reduced COE and higher TNPC for the system. The effect is portrayed in the following Fig. 16.

4.2.4. Sensitivity to primary load consumption increment on COE and TNPC

The sensitivity of COE and TNPC to the increment of Primary Energy Demand has been investigated by increasing primary load from 5–30%. Fig. 17 shows that the COE has reduced until 20% increment in the primary energy demand and any further rise results in increased COE. This is due to the fact that the additional energy is generated by BG and DG in the system and consequently, the life period of BG and DG reduces and as a result, they need to be replaced soon which incur additional costs. Conversely, TNPC increased exponentially around 7% due to the change in primary energy demand.

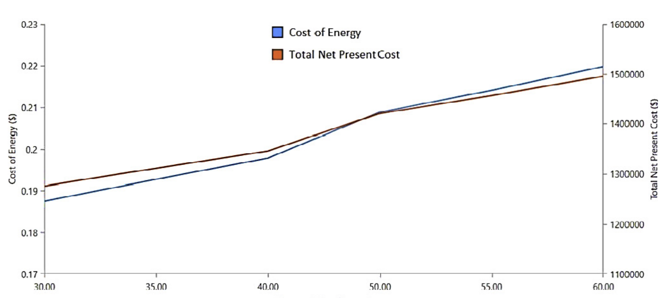

Fig. 14. Impact of biomass price variation on COE and TNPC.

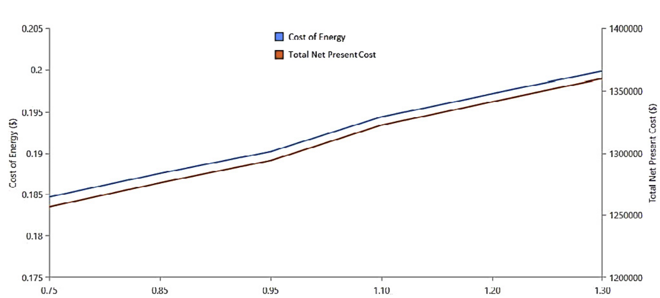

Fig. 15. Impact of diesel price variation on COE and TNPC.

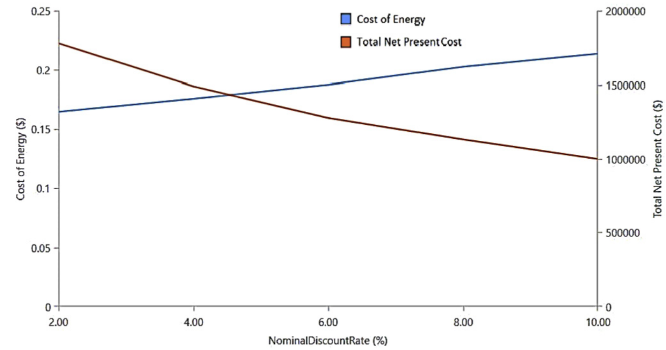

Fig. 16. Impact of discount rate variation on COE and TNPC.

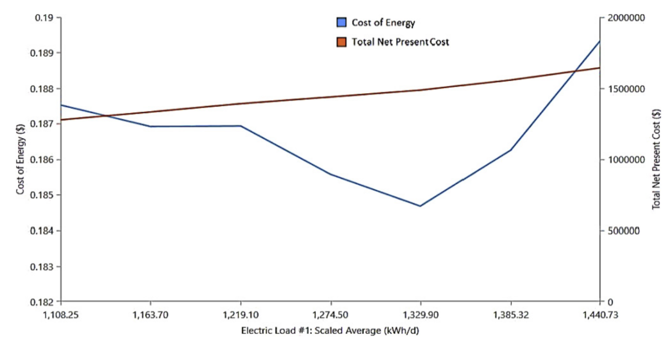

Fig. 17. Impact of primary energy variation on COE and TNPC.

4.2.5. Sensitivity to selling electricity price on payback period

In our study, we also estimated payback period for different electricity selling rate using the same methodology described in Ref. [86]. The total cost of Hybrid mini-grid Configuration-C during the project lifetime is found $1,275,888 if no capital incentives are received from the Government. The income of the hybrid mini-grid entirely depends upon the electricity selling rate to the end consumers in such case. Assuming the selling price as $0.25/kWh, around 25% higher than the generation cost, gives us a total income in 25 years around $2,705,825 with a total profit of $1,429,937 which results in a payback period of 12 years as shown in Table 10. With the selling price increment of electricity from $0.25 to $0.45/kWh, 58% higher than the production cost, increases the turnover and decreases the payback period from 12 years to 6.5 years. An additional increase in the selling price of electricity from $0.45 to $0.5/kWh, around 65% more expensive than the per unit electricity generation cost, intensifies the profit from $3,583,347 to $4,123,262, and simultaneously cuts the payback period from 6.5 years to a realistic 6 years. It is observed from Table 11 that the payback period reduces substantially with increasing rate of selling electricity price.

It is apparent that the charged tariff to obtain a reasonable PP is way higher than the regular utility electricity price. In this regard, the GoB provides a capital subsidy if the electricity tariff of hybrid mini-grid is substantially higher than the tariff charges by the nearby PBS. This subsidy can be given up to an upper limit of 60% of the capital cost of the hybrid mini-grid system [13]. Therefore, in our analysis we also determined the payback period considering

Table 11
Simple payback period estimation.

Selling price ($/kWh)	Expense ($)	Income ($)	Profit ($)	PP without subsidy (years)
0.25	1,275,888	2,705,825	1,429,937	≈ 12
0.3	1,275,888	3,246,990	1,971,102	≈ 10
0.35	1,275,888	3,778,155	2,502,267	≈ 8.5
0.4	1,275,888	4,329,320	3,053,432	≈ 7.5
0.45	1,275,888	4,859,235	3,583,347	≈ 6.5
0.5	1,275,888	5,399,150	4,123,262	≈ 6

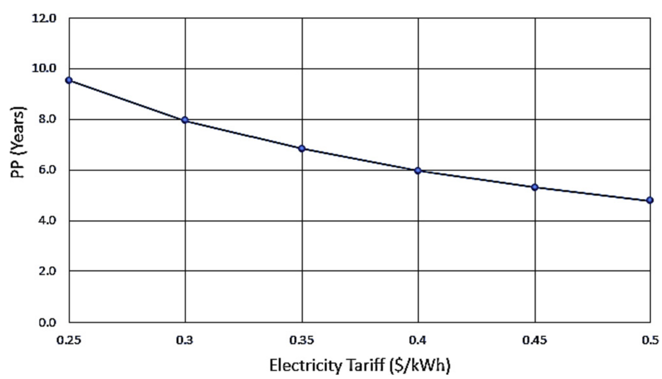

Fig. 18. Payback period with 60% capital subsidy for different electricity selling rate.

60% capital subsidy. The capital cost of Configuration-C is estimated as $ 406,692, and considering 60% subsidy the capital cost is reduced to $ 162, 676. It is evident from Fig. 18 that to reach the payback period 6 years as above, the adjusted required tariff is estimated as $0.4/kWh which is 20% less compared to the tariff without subsidy to reach the same payback period.

5. Business and financing model: strategies and challenges

This research targets to test an innovative business model around the funding and ownership of the energy system. The proposed configuration-C will ensure that the local industries can afford clean energy solution by fetching private sector investment that would otherwise not be attracted to hybrid renewable energy system development. Energy systems are offered, designed and installed based on the needs and priorities of the identified business agencies and communities.

In the targeted villages of the Debiganj Upazila dedicated local energy consumer will be identified. At least 2 rice mills, 4 small-sized industry, 2 diesel powered water pump and 10 irrigation pumps will be identified and connected to the hybrid mini-grid replacing their traditional ways of energy consumption. Resource mapping of Debiganj Upazila showed the adequate presence of energy consuming facilities and helped the authors to locate each [96].

A business model is proposed in the Fig. 19. The proposed hybrid mini-grid will be co-owned by the local business industries and a selected private company through a joint venture ownership model. The private company will provide the technology and operate the hybrid mini-grid system for 12 years (Considering PP 6 years) to sell the electricity generated to the identified agencies and nearby identified industries and households. The private company will hold an operation, management and maintenance agreement especially keeping the post-handover major breakdown, failure and maintenance in mind. A management team like “Energy Shomitte” to be formed and trained on governance, technical and financial management etc. during the operation of the private

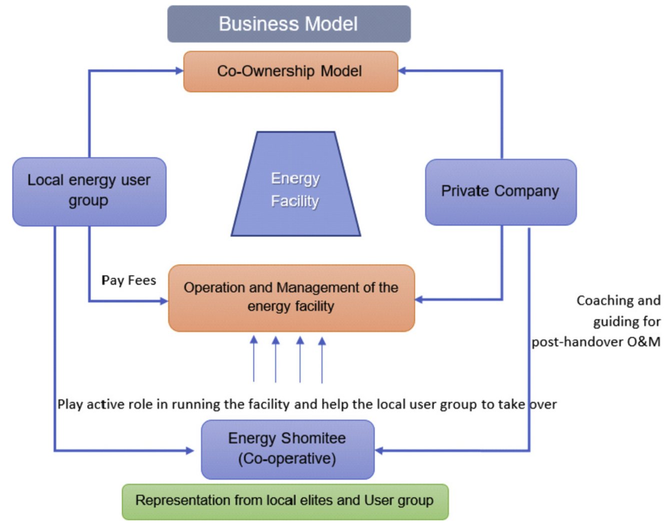

Fig. 19. Business model for the prosed hybrid mini-grid system.

company. After 12 years of operation when the investment has been recouped, the ownership of the energy system will move to the local agencies from the private company on a shareholder agreement and they will generate income by continuing to sell the excess electricity to the connected households, shops etc.

A feasibility study and user identification study at household level will be conducted to keep track of the purchasing capacity of the local energy consumers. Individual interview and geo-tagging will be done to provide more accurate information on the existing energy use within the community and energy connections to the hub. A mobile based metering and billing system linking any bank or financial institution will be introduced to permit users to pay electricity bill using mobile money, either pre- or post-usage, in an easy, convenient and transparent method. A business viable tariff (both commercial and domestic usage) will be fixed in consultation with the joint ventures and local users such as shops and households.

Focus group discussion and key person consultation will be done in order to mobilize the local public and institutions. This will help for the preparatory stage of the power plant installation i.e. land acquisition and preparation, transport of raw material, analysis of market potential, tariff fixation etc. This will also improve the awareness level of the local people and access to clean energy is expected to replace diesel and kerosene use within the identified industries and communities, reducing energy costs, increasing productivity and improving the health of all involved. By products like precipitated silica and activated carbon can also contribute toward a significant earning from the power plant. It is essential that additional income is brought to the communities not just to lift them out of poverty but to provide the means to maintain the energy systems in the long run.

There are a number of challenges involved to maintain this business model:

- Gathering the important shareholder business entities nearby the power plant location will be a real challenge. In the case of remote connections, the cost of setup and line loss should be taken into account while fixation of the special tariff.
- There need to be a strong win-win funding proposition between the private company (technology provider) and the local business agencies.
- IDCOL provided financial subsidy and the soft loan provisions must be mobilized in order to reduce the investment cost.

Around 60% of the project cost is granted to receive as a soft loan at 6% interest rate and rest 40% hard investment makes the initial investment easier for the both party.
- Land acquisition in the project location takes time and if involves replacement should be taken into account seriously.
- Community involvement and creation of awareness for the improved electricity consumption for better lives may be hampered by the initiatives such as “Solar for All” under the Test Relief (TR) and Kabikha (Food for Work) programs of GoB.
- Using the energy saving appliances along with the production of clean energy is crucial to keep the market rolling on. The consumers must be adequately mobilized and made aware of the usage of such appliances and increased self-life of the products.

6. Discussion and conclusion

Our findings suggest that Hybrid mini-grid is the answer to electrify rural areas with the lowest generation costs compared to the diesel supply or standalone solar home system. However, as mentioned earlier, the utility grid tariff is $ 0.065/kWh in Bangladesh currently. In order to reach the grid parity, government incentive policy is required. Without such assistance, Hybrid mini-grid system could not reach grid parity or perform competitively, which may unfavorably affect the proposed plant. At this point, we would like to mention that from our analysis we also find out that providing even 100% direct capital subsidy from government reduces the per unit electricity cost only around 20%, leaving it still far matching from the grid parity. This finding behaves similar to the study done by Bhattacharyya (2015) of supplying electricity to an off-grid area of Bangladesh [17]. To reach the grid parity, certain operating subsidy will be required, and this can be applied restricting only to underprivileged consumers to reduce overall subsidy spending while others may be charged at the levelized rate or higher. Remarkably, one recent study done by Alam and Bhattacharyya (2017) finds that the average maximum willingness to pay by the rural customers is $0.432/kWh for electricity supply from the renewable hybrid mini-grid in Bangladesh [87]. Furthermore, from several studies it is found that in many countries rural people are highly eager to pay higher electricity prices considering the benefit it brings [88,89]. The grid supplied energy prices in Bangladesh is highly subsidized and this affects the competitiveness of renewable energy. The GoB must impose comprehensive energy policy towards rural electrification through renewable energy based hybrid mini-grid. Lack of supporting policy from GoB such as recently imposed 10% import duty on solar panels will hurt the renewable energy based hybrid mini-grid and such initiative's will face a setback. The government must remember that the rural electrification through hybrid mini-grid projects not only produce many jobs locally for underprivileged inhabitants but also excel the productivity and quality of life. Thus, an adaptation of the most important policy framework such as finance program identical to the efforts of IDCOL taken for SHS in rural areas could aid swift adoption of renewable based hybrid mini-grid. In this regard, we would like to mention that mini-grids installed in India under the Remote Village Electrification Programme (RVEP) and the Village Energy Security Programme (VESP) have been heavily subsidized by the government and it is reported that for rural areas, 90% of the project expenses have been met by subsidies from the central government and such projects are running efficiently [90]. The cumulative outcomes of our proposed hybrid mini-grid system in the studied rural areas are summarized as follows:

- Power sector of Bangladesh is vulnerable due to the high fuel crisis and also the fact that connecting large number of rural areas into grid requires a huge investment which is not affordable at this stage of its economic development. Solar photovoltaic and biomass has the possibility to be used extensively in rural off-grid areas.
- PV/Biomass/Battery/Diesel hybrid mini-grid system (Configuration-C) is found as an optimum system. Per unit cost of energy is estimated for the optimized system as $0.188. It is also observed that configuration-A has comparable COE ($ 0.20/kWh) and higher REF which means lower emission, but it also incurs higher capital cost and total NPC.
- The highest portion of electricity in the optimal system is produced from the biomass generator and it delivers power to the studied area with a reasonably lower price using locally accessible bio resources. The share of electricy generation by the biomass generator, the PV system, and diesel generator are 54.6%, 38.3%, and 7.1%, respectively while the renewable energy penetration stands at 92.9%.
- The designed hybrid mini-grid energy system generates CO_2 emissions of 31, 054 kg/yr and it cuts the emission of CO_2 by 91% compared to diesel-only supply system, 89% than the grid supply system and 75% lower than fulfilling energy needs by using kerosene.
- Considering the selling electricity tariff of $0.25/kWh, the payback period for the proposed system is found as 12 years. The results confirm that with increasing the selling price of electricity would increase the profit and lessen the payback period accordingly.
- Sensitivity analysis shows that the proposed system is most prone to variability of biomass cost as most of the energy is harvested from biomass generator. Rising price of biomass resource and diesel increases the per unit energy cost thereby increasing the TNPC of the system.
- The proposed hybrid mini-grid system needs high capital and replacement costs; our analysis finds that government subsidies in the form of capital and operational subsidies are required to reach grid parity which in return will boost investments in renewable energy, create jobs, reduce poverty and solve rural electrification problems to a great extent.
- Several rural hybrid energy system business models are being tested and operated currently around the world [See Refs. 91–93 for example]. Our proposed co-funding and the co-ownership business model is the adoption of these models. We also identified a list of challenges in our proposed business model. Finding investor for installing a hybrid mini-grid system for low income people in rural areas is the most critical challenge.

Implementing this sort of projects in the rural areas have political, economic and socio-economic challenges but the welfares of electrifying rural areas are far more significant for enhancing the quality of life. It is therefore the responsibility of the Government and other financial organizations to come forward to support and encourage these kinds of rural electrification projects. In this study, we have concisely considered and assessed the financing challenge, business model choice, electricity selling rate while going beyond the techno-economic analysis. As the consumers are inhabitants of rural areas so majority of them are illiterate, vulnerable and lack the knowledge of renewable energy benefits. The high tariff of electricity can refrain some villagers to choose renewable energy supply option. In addition, to deliver the desired level of service the investor needs to be protected and encouraged.

Finally, our study enriches the literature in rural electrification while specific attention is given to Bangladesh and it is anticipated to contribute to the knowledge of hybrid mini-grid potentiality in Bangladesh. The study may act as a source that offers and reveals the insights on the potentiality of implementing renewable energy based hybrid mini-grid in the rural unelectrified areas to the government and further local or international stakeholders and points out on what crucial drivers need to be emphasized. To conclude, we recommend few areas for further exploration: investigation of the details of mini-grid management as the system is highly penetrated by renewable energy; the details social, technical and economic barriers of rural hybrid mini-grid; investigate on further potential business models specifically for clean energy prioritized rural grids in Bangladesh and south-east Asia; investigate the economies of scale for further extending the hybrid mini-grid in nearby areas; interviewing relevant national/international acting agencies in this field to know their challenges and key drivers for success, and study on a country level of the suitability of the proposed rural electrification approach.

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Author contributions

Md Shahinur Islam designed this research article, performed the system modeling and wrote most of the parts of this manuscript. Ruma Akhter contributed by writing the biomass, and business and financial model part of the article and also provided a number of key suggestions. Md Ashifur Rahman was mainly responsible for drawing a number of figures, and manuscript editing.

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Annex A

Optimization results table showing the system parameters for Configuration-C sorted by TNPC.

Architecture					Cost			System			Dsl	Bio		PV	1kWh LA
PV (kW)	Dsl (kW)	Bio (kW)	1kWh LA	Converter (kW)	COE ($)	NPC ($)	O&M ($)	Ren Frac (%)	Elec Prod (kWh/yr)	Elec Con (kWh/yr	Productio (kWh)	Hours	Productio (kWh)	Productio (kWh)	Annual Throughpu (kWh)
103	40.0	60.0	60	77.2	$0.188	$1.28M	$6,686	92.2	476,231	431,931	33,651	6,666	260,236	182,344	7,454
103	40.0	60.0	70	81.2	$0.188	$1.28M	$6,858	92.3	477,011	431,932	33,135	6,618	260,302	183,575	9,174
106	40.0	60.0	70	88.4	$0.188	$1.28M	$6,839	92.3	479,924	431,932	33,119	6,575	258,648	188,157	9,172
104	40.0	60.0	60	92.6	$0.188	$1.28M	$6,675	92.2	478,112	431,931	33,598	6,639	259,107	185,408	7,417
101	40.0	60.0	70	88.5	$0.188	$1.28M	$6,873	92.3	474,852	431,932	33,191	6,651	261,581	180,080	9,165
103	40.0	60.0	60	98.4	$0.188	$1.28M	$6,685	92.2	476,332	431,931	33,652	6,662	260,141	182,539	7,467
104	40.0	60.0	50	73.4	$0.188	$1.28M	$6,565	92.1	478,451	431,925	34,333	6,811	259,648	184,470	4,609
102	40.0	60.0	80	85.9	$0.188	$1.28M	$7,047	92.5	475,965	431,936	32,561	6,604	261,849	181,555	10,533
104	40.0	60.0	90	76.6	$0.189	$1.28M	$7,216	92.5	477,721	431,936	32,341	6,541	261,141	184,239	11,548
99.1	40.0	60.0	70	98.4	$0.189	$1.28M	$6,887	92.3	472,388	431,932	33,265	6,685	263,262	175,861	9,303
104	40.0	60.0	80	101	$0.189	$1.28M	$7,032	92.5	477,727	431,936	32,587	6,570	260,689	184,451	10,593
102	40.0	60.0	50	96.6	$0.189	$1.28M	$6,570	92.0	476,085	431,925	34,359	6,825	260,559	181,168	4,607
104	40.0	60.0	70	116	$0.189	$1.28M	$6,849	92.3	477,641	431,932	33,125	6,599	259,837	184,679	9,275
107	40.0	55.0	60	77.1	$0.189	$1.28M	$6,537	90.0	481,065	431,887	43,259	6,912	248,549	189,258	4,477
97.0	40.0	60.0	80	89.8	$0.189	$1.28M	$7,080	92.4	470,461	431,935	32,792	6,680	265,472	172,197	10,761
107	40.0	60.0	90	93.0	$0.189	$1.28M	$7,186	92.5	481,340	431,935	32,244	6,474	258,983	190,113	11,698
106	40.0	55.0	60	77.4	$0.189	$1.29M	$6,546	90.0	479,749	431,887	43,274	6,933	249,224	187,252	4,459
97.3	40.0	60.0	60	68.2	$0.189	$1.29M	$6,777	92.2	472,025	431,931	33,754	6,857	265,651	172,620	7,444
107	40.0	55.0	60	100	$0.190	$1.29M	$6,535	90.0	481,478	431,887	43,238	6,907	248,317	189,923	4,438
125	45.0	60.0	60	71.8	$0.190	$1.29M	$6,584	92.2	502,881	431,936	33,541	6,406	248,268	221,072	7,012
128	45.0	60.0	60	97.7	$0.190	$1.29M	$6,531	92.2	506,292	431,936	33,525	6,293	245,532	227,235	7,156
87.6	40.0	60.0	80	74.1	$0.190	$1.29M	$7,175	92.4	461,775	431,934	32,972	6,888	273,277	155,526	10,823
128	45.0	60.0	70	102	$0.190	$1.29M	$6,710	92.4	505,738	431,936	32,918	6,263	246,481	226,339	8,919
108	40.0	55.0	50	82.2	$0.190	$1.29M	$6,349	89.8	482,445	431,853	43,925	6,923	246,981	191,540	3,012
129	45.0	60.0	70	101	$0.190	$1.29M	$6,704	92.4	507,884	431,936	32,882	6,248	245,798	229,204	8,853
124	45.0	60.0	90	79.4	$0.190	$1.29M	$7,091	92.6	501,742	431,936	31,930	6,244	249,565	220,247	11,696
125	45.0	60.0	60	98.0	$0.190	$1.29M	$6,552	92.2	502,343	431,936	33,553	6,341	247,143	221,646	7,126
124	45.0	60.0	70	106	$0.190	$1.29M	$6,734	92.4	500,643	431,936	32,955	6,319	248,471	219,218	8,915
129	45.0	60.0	70	70.7	$0.190	$1.29M	$6,751	92.4	509,062	431,936	32,852	6,343	247,443	228,767	8,697
98.2	40.0	60.0	50	120	$0.190	$1.29M	$6,601	92.0	472,005	431,925	34,487	6,893	263,295	174,223	4,659
127	45.0	60.0	50	79.9	$0.190	$1.29M	$6,425	92.0	505,764	431,936	34,358	6,472	246,133	225,273	4,327
94.3	40.0	60.0	90	97.4	$0.190	$1.29M	$7,289	92.4	467,873	431,936	32,633	6,705	267,881	167,358	11,630
102	40.0	55.0	60	104	$0.190	$1.29M	$6,567	90.0	476,227	431,886	43,390	6,984	251,124	181,713	4,363
128	45.0	60.0	50	76.3	$0.190	$1.29M	$6,425	92.1	507,383	431,936	34,331	6,470	245,777	227,275	4,261
122	45.0	60.0	80	70.9	$0.190	$1.29M	$6,968	92.5	500,773	431,936	32,283	6,396	251,302	217,189	10,082
108	50.0	60.0	70	84.4	$0.191	$1.30M	$6,821	92.3	482,402	431,936	33,344	6,511	256,498	192,561	9,140
129	40.0	60.0	50	72.0	$0.191	$1.30M	$6,473	92.1	503,174	431,837	34,253	6,571	240,362	228,558	5,381
120	45.0	55.0	80	86.9	$0.191	$1.30M	$6,838	90.2	496,740	431,935	42,515	6,669	241,092	213,133	6,316
129	40.0	60.0	50	96.7	$0.191	$1.30M	$6,441	92.1	502,924	431,837	34,249	6,507	239,058	229,617	5,421
129	45.0	60.0	50	109	$0.191	$1.30M	$6,415	92.1	508,931	431,936	34,335	6,449	245,100	229,495	4,250
123	40.0	55.0	60	92.0	$0.191	$1.30M	$6,362	90.1	490,100	431,346	42,830	6,483	229,468	217,801	8,212
108	50.0	60.0	70	72.6	$0.191	$1.30M	$6,839	92.3	482,123	431,936	33,407	6,547	257,299	191,417	9,142
134	40.0	45.0	40	98.0	$0.192	$1.30M	$5,544	85.1	511,727	430,123	63,922	6,721	210,759	237,046	3,496
132	40.0	45.0	50	75.3	$0.192	$1.30M	$5,747	85.2	510,853	430,527	63,691	6,738	212,406	234,756	4,586
132	40.0	45.0	40	99.2	$0.192	$1.30M	$5,552	85.1	509,730	430,122	63,982	6,744	211,415	234,334	3,482
120	45.0	55.0	70	92.6	$0.191	$1.30M	$6,645	90.0	496,576	431,935	43,004	6,676	240,556	213,016	5,289
130	40.0	60.0	60	70.7	$0.191	$1.30M	$6,587	92.4	501,223	431,861	32,876	6,405	237,890	230,458	9,264
107	50.0	60.0	80	73.7	$0.191	$1.30M	$7,029	92.4	480,825	431,936	32,695	6,539	259,105	189,025	10,601

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