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Electricity from Wind for Off-Grid Applications in Bangladesh: A Techno-Economic Assessment

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ABSTRACT. Global GHG (greenhouse gas) emissions are increasing substantially and electricity sector is one of the key contributors to the world's total GHG emissions. GHG emissions cause ozone layer depletion and global warming. Different policy regulation agencies are adopting regulations to reduce GHG emissions in various sectors. People already have started power generation from cleaner sources. Renewable energy sources can provide cleaner electricity. Bangladesh is a densely populated country and most of the country's electricity is produced from natural gas and coal. The Bangladesh government has set a goal to utilize renewable energy for the production of 10% of its electricity by the year 2020. Bangladesh has a lot of isolated coastal areas which are not connected to the national grid which can be electrified by using abundant wind energy. In this study a techno-economic analysis has been conducted for an off-grid island of Bangladesh. The analysis was conducted by developing a data intensive model that calculates the generation cost of electricity from wind energy. The model also estimates the capital cost of the system. The model shows that electricity can be produced from wind energy at a cost of $0.57/kWh. The system's capital cost was calculated to be $63,550.16.

Keywords: GHG emission, cost of electricity, off-grid, wind energy, electricity generation.

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1. Introduction

Environmental concerns and international agreements to reduce the atmosphere's greenhouse gases and minimizing dependency on the fossil based non-renewable fuels are the most important reasons behind the increased interest in renewable energy resources in recent years (Khan, Hawboldt, & Iqbal, 2005). About 60% of the total greenhouse gases emitted in the environment is caused by energy generation from fossil fuels (IEA 2009). United States being the largest consumer (almost 50% of the world's total energy consumption) releases 22% of the carbon-di-oxide by combustion of fossil fuels (Pimentel et al., 2002; Turner, 1999). The reserves of fossil fuels are also reducing at an alarming rate at the same time. For example, USA having consumed 82-88% of the oil reserves, now imports 60% of its oil and it is predicted that within 20 years they will have to import 80-90% of its oil (American Petroleum Institute. 1999. Basic Petroleum Data Book. Washington (DC): API). Same is the scenario for most of the countries around the globe. Therefore, many countries are adopting renewable energy in place of conventional fuels for electricity generation. The United Nations expects 30% of the world's need of energy to be covered by renewables by 2030 and 45% by 2050 (IEA. Key issues in developing renewable. Paris: International Energy Agency, 1997). As of 2014 the world's power generation capacity from the renewable sources was 1712.20 GW ("REN21. Renewables 2015 Global Status Report,"). A comparison of source wise capacity of power generation from different renewable sources in 2004 and 2014 is shown in Table 1. The growth of power generation from solar PV and wind was tremendous (see Table 1).

However, in Bangladesh only 3.45% of 12,262 MW of total installed capacity of electricity generation is obtained from renewable sources as of April 2016, whereas 62% of the total capacity comes from natural gas ("Bangladesh Power Development Board,").

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Tabel 1
The world's power generation capacity from renewable sources. Source: Ref. ("REN21. Renewables 2015 Global Status Report,")

Renewable source	2004 (GW)	2014 (GW)
Hydro power	715	1055
Bio power	<36	93
Geothermal power	8.9	12.8
Solar PV	2.6	177
Concentrating solar thermal power	0.4	4.4
Wind power	48	370

The breakdown of the installed power generation of Bangladesh by source is shown in Figure 1. By 2020 the electricity generation from renewable sources in Bangladesh is expected to be 10% of the total capacity although the expected 5% within 2015 is not achieved. Per capita generation of electricity in Bangladesh is very low, which is about only 258 kWh/year ("The world Bank,"). Only 53% of the population is taken under electrification. To deal with the increasing demand of electricity several measures to harness energy from renewable sources are being taken by the government and several organizations including IDCOL (Infrastructure Development Company Limited), Grameen Shakti (which is a sister organization of the Grameen Bank), etc. These organizations mainly work with propagation of renewable energy technologies in Bangladesh. The government has launched a project to produce 500 MW of electricity from solar power, whereas IDCOL is working to install 6 million solar home systems (SHSs) by 2017 ("IDCOL, Infrastructure Development Company Limited," ; "Power Division. Government of The People's Republic of Bangladesh,"). The current power generation scenario of Bangladesh from renewable sources is shown in Table 2.

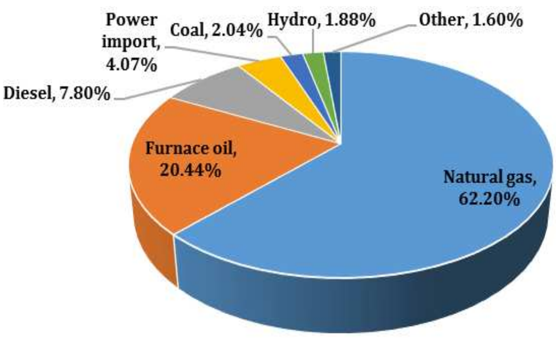

Figure 1. Breakdown of installed electricity generation capacity of Bangladesh by source. Source: Ref. ("Bangladesh Power Development Board,")

Table 2
Installed renewable energy technologies in Bangladesh. Source: (Sustainable & renewable energy energy development authority (SREDA))

Renewable energy technology	Off-grid (MW)	On-grid (MW)	Total (MW)
Biogas to electricity	5	-	**5**
Biomass to electricity	1	-	**1**
Hydro	-	230	**230**
Solar PV	184	1	**185**
Wind	1	0.9	**1.9**
Total	**191**	**232**	**423**

Although wind energy is not so promising as other renewable energy systems since it is limited to rivers sides, coastal areas, offshore islands and other inland open areas with strong wind regime but wind has the lowest GHG emissions, with only around 25 g-CO_2eq/kWh and is a fast growing renewable energy technology (Evans, Strezov, & Evans, 2009). From 1980 to 2005 the cost of electricity generated from wind has been reduced from 20 eurocents to 3.7 eurocents (Mathew, 2006). The reduction in the price resulted in increased interest in wind energy systems and it is assumed that by 2030 the installed capacity of wind energy will be 100,000 MW in Europe and by 2020 worldwide capacity of wind energy will be 180-474 GW (Akpinar & Akpinar, 2006). The global wind power generation capacity has been increasing substantially. The electricity generation from wind is increased by 118% from 2010 to 2015. The global wind power addition was 51 GW in 2014 and 63 GW in 2015 and reached a total capacity of 432 GW. The global wind power generation capacity from 2000-2015 is shown in Figure 2.

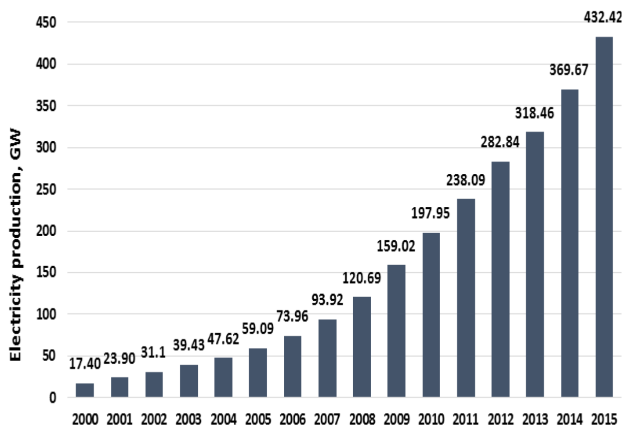

Figure 2. Global cumulative installed wind capacity from 2000 to 2015. Source: Ref. ("GWEC. Global Wind Energy Council,")

In Bangladesh two wind plants have been installed of 900 kW and 1000 kW at Sonagazi and at Kutubdia Island, respectively ("Bangladesh Power Development Board,"). But due to natural calamities these plants are left unutilized. Anyway recently the government has taken steps to recover these plants and in addition, a 15

MW wind power plant is under construction across the coastal region of Bangladesh. Bangladesh Power Development Board (BPDB) has another 50-200 MW wind energy project, which is under planning (Bangladesh Power Development Board).

Several studies have conducted the techno economics of stand-alone wind energy systems. Celik (Celik, 2007) analysed the technical and economic assessments of wind energy in southern Turkey. The author found that the lowest cost of electricity with the nominal power of 500 kW was $0.15/kWh and it was very close to Turkey's electricity production from conventional sources which is $0.13/kWh. Chong et al. (Chong, Naghavi, Poh, Mahlia, & Pan, 2011) on the other hand introduced solar with wind energy and suggested a system to supply power to a high rise building which utilizes a power-augmentation guide vane to channel wind to the turbine. The techno-economic analysis of this system estimates the energy saved by the system to be 195 MWh/year. PV, hydro and diesel were introduced with wind energy in HOMER software by Sopian et al. (Sopian, Ali, Alghoul, Zaharim, & Ahmad, 2009) to simulate the cost of production of energy. The authors suggest that it is possible to minimize the cost by 50% with maximum demand load capacity. Ahmed et al. (Ahmed, Miyatake, & Al-Othman, 2008) designed a system consisting of variable speed wind turbine, fuel cell and solar photovoltaic to supply continuous power to a residential building where wind and photovoltaic were the main energy sources and fuel cell was the backup energy source. The system was designed to power a 2 kW/150 V load continuously for the whole year and the result shows that even if there is no wind or sunlight the system provides full power to the load. Li et al. (Li et al., 2013) studied a photovoltaic (PV)/wind/battery hybrid power system and found that the system reduces the net cost by 9% and 11% compared to photovoltaic/battery and wind/battery system, respectively. In the system they have used 5 kW of PV arrays, one 2.5 kW wind turbine and 8 batteries each of 6.94 kWh. Muralikrishna and Lakshminarayana (Muralikrishna & Lakshminarayana, 2008) found the energy cost for PV-wind hybrid system to be less than the stand-alone PV or wind system all the time. There have been number of studies that design hybrid renewable energy systems and estimate the cost of electricity for various regions around the globe (Abdulkarim, 2004; Adaramola, Agelin-Chaab, & Paul, 2014; Chandel, Agrawal, Mathur, & Mathur, 2014; Fadaeenejad, Radzi, AbKadir, & Hizam, 2014; Ghasemi, Asrari, Zarif, & Abdelwahed, 2013; Kusakana & Vermaak, 2013; Ngan & Tan, 2012; Md Mustafizur Rahman, Khan, Ullah, Zhang, & Kumar, 2016; Rehman & Al-Hadhrami, 2010; Rohani & Nour, 2014). The cost of electricity depends on various factors such as resource availability (e.g. solar insolation, wind speed, etc.), price of components, project interest rate, lifetime of projects, etc. Islam et al. (Islam, Rahman, Mondal, & Alam, 2012) analysed the techno-economic aspect of a hybrid system for Saint Martin's Island, Bangladesh. The authors found the COE (cost of electricity) to be $0.345/kWh. Salehin et al. (Salehin, Rahman, & Islam, 2015) designed a solar PV-diesel generator system for an off-grid location in Bangladesh with a COE of $0.461/kWh. Rahman et al. (Md. Mustafizur Rahman, Islam, Salehin, & Al-Matin, 2016) performed a techno-economic analysis of a stand-alone PV system for application in an isolated community in Bangladesh. The COE was calculated to be $0.72/kWh.

Since the wind energy field in Bangladesh has got less attention compared to solar, hydro and biomass, there is lack of information regarding the parameters related to the economics of power generation from wind energy. Fewer studies have conducted the techno-economic analysis of hybrid renewable energy systems (different combinations of solar PV-wind-diesel, etc.) and stand-alone solar PV systems for isolated communities in Bangladesh but assessment of wind energy for power generation is very limited. There have been studies on techno-economic assessment of wind power in various countries but these are not applicable for Bangladesh as designing a renewable energy system and estimating the cost of electricity are very much location-specific. The main objectives of this research are (i) to design a wind energy system for electricity generation for an isolated off-grid community in Saint Martin's Island, Bangladesh and (ii) to conduct a techno-economic assessment of the designed system by developing an excel-based bottom-up engineering model that can estimate the capital cost and the electricity generation cost. The proposed power generation system using wind energy will replace the existing diesel generator system for the selected location. The present study also shows how much GHG emissions could be reduced if the diesel-fueled generators are replaced by the wind turbines. An analysis is also performed to find out the sensitivity of the most influential inputs that can affect the results.

2. Methodology

This study carries out a techno-economic assessment (TEA) of electricity generation from wind energy resource. Firstly, a stand-alone wind turbine system was designed to fulfill the demand of electricity of a community consisting 50 households in the Saint Martin's Island, Bangladesh. Then a TEA was conducted to estimate the capital cost and the COE of the system. The techno-economic assessment was conducted by developing an excel-based data-intensive technical model. The model considers all the components of the wind energy system for power generation. The system boundary used for this study is depicted in Figure 3. The components of wind power generation system includes one or more wind turbine(s), a turbine controller for converting the AC current produced by the wind turbine(s) to DC current which is to be stored in the bank of batteries.

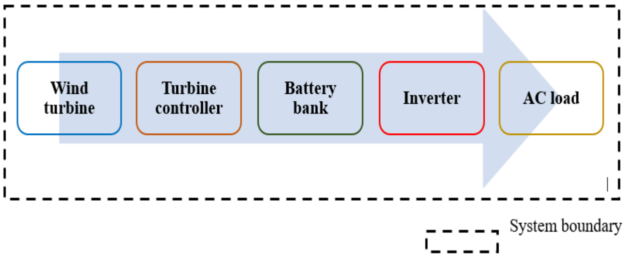

Figure 3 System boundary used for this study

The inverter alters the direct current (DC) coming out of the battery bank to alternating current (AC). This research also includes the component's installation and maintenance costs and cost of civil works within its system boundary. The transmission system (e.g. copper cables and pillars to carry the cables) were not considered within the system boundary. It was assumed that the existing transmission system will be used for the proposed power generation system from wind. Figure 4 represents the methodology used for estimating the cost parameters related to the production of electricity from wind energy. The functional unit was considered as 1 kWh AC electricity and all the cost numbers are in 2015 US dollars unless otherwise mentioned.

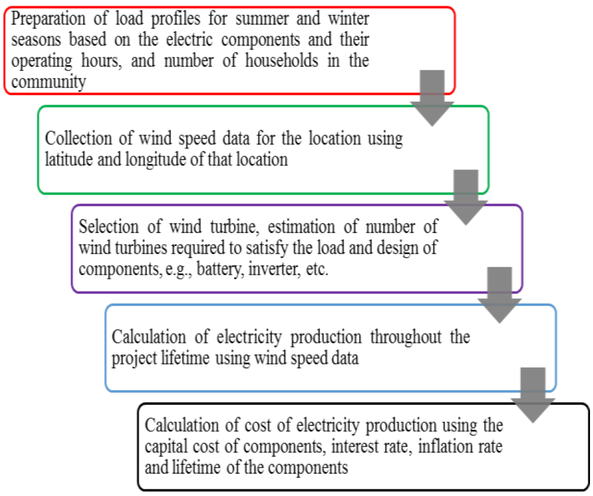

Figure 4. Modelling methodology developed for this study

The location, Saint Martin's Island was selected due to the availability of wind energy throughout the year. The electric load demand was estimated for summer and winter seasons separately based on the total number of electric equipment per household and their operating hours and the total number of households in the community. Wind data throughout the year were collected from NASA surface meteorology website ("Surface meteorology and solar energy,") using the location's latitude and longitude values. Then sizing of all the components (e.g. wind turbine, battery, inverter, etc.) was done to meet the load demand. The electricity production was estimated throughout the project life depending upon the data of wind speed of the location. Finally, the cost numbers (e.g. capital cost and COE) were calculated using the capital cost of each component and their useful life, interest rate and inflation rate.

2.1 Site selection and load calculation

2.1.1 Site description: Saint Martin's Island

The Saint Martin's Island was selected for the analysis as this place has significant wind energy potential for power generation which can replace the existing power generation method (i.e. diesel generators). The island is situated in the north-eastern side of the Bay of Bengal and from cox's bazar-saint Martin peninsula almost 9 km to south (Islam et al., 2012). The geographical coordinates of the island are 20.63 °N and 92.32 °E (Islam et al., 2012). The total population of the island is around 7500 and fishing is their main profession ("Saint Martin Coral Island, Bangladesh,"). The total area of the island is 8 km^2 (Ahammed, Hossain, Abedin, & Khaleque, 2016). An aerial view of the island is depicted in Figure 5. The island is separated from the national grid of Bangladesh. The residents of the island produce their own electricity using diesel generators and the fuel for the generators is transported through ships from the main land of Bangladesh to the island which raises the cost of fuel and in turns cost of electricity is increased. On the other hand burning diesel releases greenhouse (GHG) gases into the atmosphere which causes global warming. Saint Martin's Island has good wind energy potential that can be used to generate electricity using wind energy.

Figure 5. An aerial view of the Saint Martin's Island, Bangladesh. Adapted from ref. (Islam et al., 2012)

2.1.2 Estimation of electric load

Usually the load profiles of rural communities are very simple. Electricity consumption in rural communities is very low compared to urban communities. A typical household in rural communities uses few LED bulbs for lighting, a small television for entertainment and one or more ceiling fans for cooling purpose (Md. Mustafizur Rahman et al., 2016). In this study, 5 LED bulbs (3 W each), an LCD television (18 W) and 2 ceiling fans (24 W each) were considered. Fans are only used in the summer season. The daily operating hours for lights, television and fans were considered to be 8 hours, 6 hours and 10 hours, respectively. Two different load profiles for a hypothetical model community of fifty houses were created for winter (November-March) and summer (April-October) seasons. The average electricity consumption for the community was 11.4 kWh/day and 35.4 kWh/day for winter and summer, respectively. The peak load in summer season was estimated as 4.05 kW. The total load throughout the year was found to be 9.144 MWh.

2.2 Assessment of wind energy and electricity generation

The wind speed data were obtained from NASA surface meteorology and solar energy website ("Surface meteorology and solar energy,") using the latitude and longitude of the island. Figure 6 represents the monthly averaged wind speed data at 50 m height for Saint Martin's Island. Wind speed is high in June, July and August. In December the wind speed was minimum (3.64 m/s) and in July it was maximum (7.43 m/s). The yearly average wind speed was 4.85 m/s.

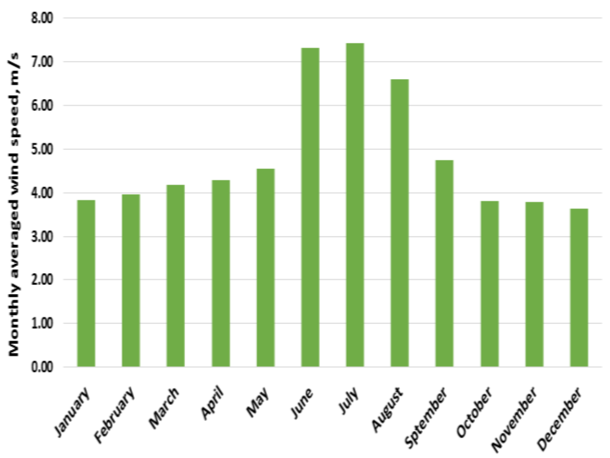

Fig. 6 Wind speed variation throughout the year in Saint Martin's Island, Bangladesh

Any place does not get the same wind speed round the clock throughout the year. So to find out the mean power from a turbine it is important to find the probability distribution of wind speed (Md Mustafizur Rahman et al., 2016). The Weibull distribution expression is shown in (Eq 1) (Bhuiyan, Islam, & Alam, 2013) which shows a good fit to wind data. In (Eq 1), f (V) is probability density function, (k) is the Weibull shape factor, (c) is the scale factor and (V) is the wind velocity.

$$f\,(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \qquad (1)$$

Here, k and c were calculated from the monthly mean wind velocity for the selected location using the Web Based Wind Resource Assessment (WEA) Tool (Bhuiyan et al., 2013). Given the mean wind velocity of 4.85 m/s, a wind turbine was selected for this research based on the cut-in speed and rated power: a 3.2 kW wind turbine of model W175 manufactured by Unitron South West Windpower, USA (Nouni, Mullick, & Kandpal, 2007). A hub height of 50 m was assumed in this study (Md Mustafizur Rahman et al., 2016; Verma, Raj, Kumar, Ghandehariun, & Kumar, 2015). The cut-in speed and the rated speed of the turbine are 2.5 m/s and 11 m/s, respectively. All the other specifications of the turbine is presented in Table 3. The WEA tool was used to estimate the electricity production and the capacity factor using shape factor, scale factor, cut-in speed, cut-out speed, rated speed, ideal velocity power proportionality and total operating hours (8760 hours) in a year.

Table 3
Technical specifications of the wind turbine selected in this research

Parameter	Value	Comment/source
Size of the turbine, kW	3.2	(Nouni et al., 2007)
Rotor diameter, m	4.65	(Nouni et al., 2007)
Rotor swept area, m^2	16.98	(Nouni et al., 2007)
Cut in wind speed, m/s	2.5	(Nouni et al., 2007)
Cut out wind speed, m/s	21.0	(Nouni et al., 2007)
Rated wind speed, m/s	11.0	(Nouni et al., 2007)
Hub height, m	50	Wind speed data are available for 50 m height. Most of the studies work with 50 m hub height (Md Mustafizur Rahman et al., 2016; Verma et al., 2015)

2.3 Design of the power generation system

The system components are wind turbine, turbine controller, inverter and battery bank (see Figure 3). These components were designed using the fundamental engineering principles to meet the load demand of 9.144 MWh/year. The number of wind turbines was estimated using the load demand during summer to avoid any capacity shortage and the effective energy generated by a 3.2 kW wind turbine. The turbine controller converts the AC output from the turbine to DC input to the battery storage system. Wind speed is not continuous round the clock throughout the year. There are no or less windy days when power generation from wind is not possible. So, there is a necessity to store the electricity for sufficient time period without adequate electricity supply. The battery capacity was estimated using (Eq 2) ("Leonoics,") where the total battery capacity, (BC) is in Ah, the peak load demand during summer, (L), is in Wh/day, depth of discharge, (DD) is in %, number of days of autonomy, (D), is in days, charging efficiency, (η_c) is in %, the nominal voltage of each battery (V) is in volts.

$$BC = (L \times D)/(DOD \times \eta_c \times V) \quad \textbf{(2)}$$

In this research, (DD), (D) and (η_c) were assumed as 80% (Verma et al., 2015), 2 days and 85% (Md. Mustafizur Rahman et al., 2016), respectively. 130 Ah capacity and 12 V batteries were selected for the analysis due to their availability in the local markets (Md. Mustafizur Rahman et al., 2016). To convert the DC electricity coming from the battery bank to AC electricity to be used in the appliances an inverter is required. An inverter is designed based on the maximum demand of the system. The peak load of the system was estimated to be 4.05 kW. For designing the inverter a safety factor of 30% was used (Md. Mustafizur Rahman et al., 2016). A 5.27 kW inverter is required to safely operate the system.

2.4 Techno-economic assessment model

A techno-economic model was built to estimate the COE of the system. The year 2015 was selected as the base year and all the cost numbers are based on 2015 US dollars unless otherwise stated. The capital cost consists of costs of the turbine with tower and controller, battery bank, inverter, and costs of installation and civil works. The capital costs of the system components were amortized with an interest rate of 10% (Zubair, Tanvir, & Hasan, 2012) over the useful life of each component. The project lifetime was assumed 20 years (Ajayi, Ohijeagbon, Aasa, & Omotosho, 2014; Dursun, Gokcol, Umut, Ucar, & Kocabey, 2013; Fleck & Huot, 2009). The cost data that are not in 2015 USD were inflated using an inflation rate of 7.30% ("Bangladesh Bank,"). The conversion rate from USD to Bangladeshi Taka (BDT) was considered to be 77 (Md. Mustafizur Rahman et al., 2016). The yearly maintenance cost was considered 2.0% of the capital cost (Md. Mustafizur Rahman et al., 2016). The technical parameters and assumptions used to develop the model are furnished in Table 4.

The COE was evaluated from the system's total annual cost and the annual electricity produced by the wind turbine facility. The annualized cost was estimated considering the capital costs of all the system components and the yearly maintenance cost. (Eq 3) was used to calculate the cost of electricity (COE) (Nouni et al., 2007), where C_T (\$), C_B (\$), C_I (\$) and C_C (\$) represent the capital costs of wind turbine including controller and tower, battery bank, inverter and installation and civil works, respectively. C_M (\$/year) represents the yearly maintenance cost of the system. R_T, R_B, R_I and R_C represent the capital recovery factors for wind turbine, battery bank, inverter and civil works, respectively. The yearly electricity production is represented by EL (kWh/year).

$$COE\left(\frac{\$}{\text{kWh}}\right) = \frac{C_T R_T + C_B R_B + C_I R_I + C_C R_C + C_M}{E_L} \quad (3)$$

Table 4
Key assumptions and technical parameters for the techno-economic modelling

Parameter	Value	Comment/source
Interest rate, %	10	(Md. Mustafizur Rahman et al., 2016; Zubair et al., 2012)
Inflation rate, %	7.30	2014 annual average inflation rate. Obtained from ("Bangladesh Bank,")
Wind turbine		
Rated power, kW	3.2	(Nouni et al., 2007)
Lifetime, years	20	(Fleck & Huot, 2009; Nouni et al., 2007)
Capital cost (including controller and tower), \$/kW	5030.82[a]	Inflated for the year of 2015 (Nouni et al., 2007)
Lead-acid battery bank		
Capacity (each), Ah	130	(Md. Mustafizur Rahman et al., 2016)
Nominal voltage, V	12	(Md. Mustafizur Rahman et al., 2016)
Depth of discharge (DOD), %	80	(Verma et al., 2015)
Charging efficiency (η_c), %	85	(Md. Mustafizur Rahman et al., 2016)
Capital cost, \$ (each 130 Ah, 12 V battery)	155.84	("BD Stall,")
Lifetime, years	5	("Lead battery recycling in Banladesh," ; Yang, Wei, & Chengzhi, 2009)
Inverter		
Capital cost, \$/kW	277.08	Inflated for the year of 2015 (Alam Hossain Mondal & Sadrul Islam, 2011)
Lifetime, years	10	(Md. Mustafizur Rahman et al., 2016)
Installation and civil works		
Capital cost, \$/kW	349.37[b]	Inflated for the year of 2015 (Nouni et al., 2007)
Lifetime of civil works, years	20	(Md. Mustafizur Rahman et al., 2016)
Yearly maintenance cost, %	2.0	2.00% of the total capital cost (Md. Mustafizur Rahman et al., 2016; Verma et al., 2015)

[a]The value is calculated from (cost of a 3.2 kW wind turbine with controller and tower is Rs. 463,000 in 2003) (Nouni et al., 2007).
[b]The value is calculated from (cost of civil works and installations is Rs. 10,500 for a 1 kW turbine in 2004) (Nouni et al., 2007).

3. Results and discussion

3.1 Techno-economic assessment

Based on the wind velocity for the location under study a 3.2 kW wind speed was selected. The wind speed of the island varies from 3.64-7.43 m/s. Using the monthly average wind speeds WEA tool (Bhuiyan et al., 2013) estimates the Weibull shape factor (k) and shape factor (c) as 1.936 and 5.527 m/s, respectively. The WEA tool also calculates the electrical power generation by the system using the Weibull shape factor, scale factor, rated speed, cut-in speed, cut-out speed and yearly operation hours. The electricity production was estimated to be 6.023 MWh/year using a 3.2 kW wind turbine. To satisfy the calculated load, three 3.2 kW wind turbines are required. The total electricity production from three 3.2 kW wind turbines is 18.07 MWh/year. To store the required electricity battery bank is required. The capacity of battery bank was estimated using (Eq 2). The total battery capacity was estimated to be 8676.46 Ah and to satisfy this capacity a total of sixty seven 130 Ah lead-acid batteries are required. To alter the direct current in to alternating current which is to be fed to the load side a 5.27 kW inverter is required.

Once the system design was completed to meet the demand of the island, an economic analysis was done to estimate the total capital cost and the COE. Considering \$5030.82/kW for the wind turbine capital cost of three 3.2 kW wind turbines was estimated to be \$48,295.824. At \$155.84/battery, sixty seven batteries (130Ah, 12 V each) require \$10,441.56. The capital cost of the inverter and civil works and installation were calculated to be \$1458.81 and \$3353.97, respectively. The system's total capital cost was calculated as \$63,550.16 or BDT 4893362.22. Figure 7 delineates the capital costs of the components of the wind turbine system.

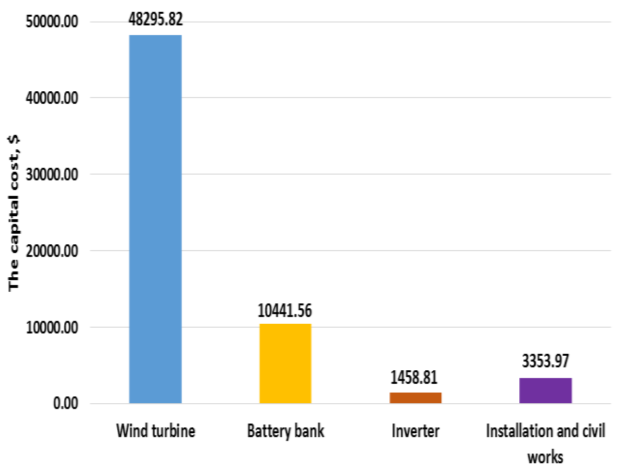

Figure 7 The capital cost distribution for the system. Base year-2015

The amortization of all the capital costs were done over the component's life time using an interest rate of 10% (see Table 4). Table 5 represents the values of the economic parameters of the system. The total annualized cost was calculated as \$10,329.64/year or BDT 795,382.23/year for the system. Wind turbines and battery bank are the most expensive elements of the system. Figure 8 shows the break-up of the total annualized cost of the system. The capital cost of the wind turbines is the highest but the turbines have a longer lifetime of 20 years. It can be noticed that wind turbines and battery bank contribute 54.92% and 26.67% of the total annualized cost followed by yearly maintenance with about 12.30% (see Figure 8). The COE is the ratio of total annual cost of the system to the total electricity generation by the system. The COE was estimated as \$0.57/kWh or BDT 44.02/kWh.

Table 5
The annual costs of different components of the system. Base year-2015

Parameter	Value	Comment/source
Number of turbines required	3	Calculated from the electricity requirement of the community and effective electricity delivered by one turbine.
Annualized cost		
Wind turbine, \$/year[a]	5672.81	Considering three 3.2 kW turbines
Battery bank, \$/year[a]	2754.46	See (Eq 2) for sizing of battery bank
Inverter, \$/year[a]	237.41	
Installation and civil works, \$/year[a]	393.96	
Total maintenance, \$/year	1271.00	Refer to Table 4

[a] The value was amortized over the lifetime

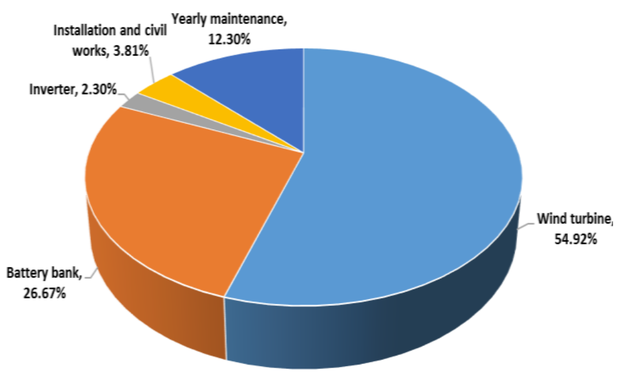

Figure 8 Annual cost break-up of the system

As the system is designed to satisfy the peak summer load there will be some excess electricity that can be used if there is any sudden increase in load demand.

The excess power also can be used for satisfying the deferrable loads (Adaramola et al., 2014).

The proposed power generation system is able to generate electricity at a cost of $0.57/kWh. The COE of the wind-based power generation system was compared with the COE of diesel power generation system. Several research have studied the techno-economic analysis of power generation from diesel fuel using diesel generators in communities which are not connected to the grid in Bangladesh. Salehin et al. (Salehin et al., 2015) conducted an economic assessment of hybrid system and only diesel generator system for an off-grid community. The authors estimated the COE for diesel generator power production system to be $0.423/kWh at a diesel cost of $0.90/litre. Another study by Shezan et al. (Shezan, Salahuddin, Farzana, & Hossain, 2016) estimated the COE for diesel generator system as $0.61/kWh for the Saint Martin's Island. It can be observed that the COE of the proposed wind power generation system is lower than the COE of the existing diesel-fueled system.

The cost of electricity (COE) of this study was compared with the COE of other earlier studies in the literature for wind power generation system (Ajayi et al., 2014; Genc, 2010; Khadem, 2006; Nouni et al., 2007; Ohunakin, Oyewola, & Adaramola, 2013). Table 6 shows the comparison of COE among the studies. The COE estimated in the present study is very close to the range of COEs reported by Khadem (Khadem, 2006). The variation of results among the studies is mainly due to various system boundaries considered in the studies. The other reasons of variation are the scale of operation and various assumptions used in the studies. Usually COE is low for larger wind turbines and vice versa. Some of the studies do not consider all the system components. Despite of these variations the COE of this study is close enough with the studies in the literature.

Table 6
Comparison of cost of electricity (COE) reported in various studies

Location	COE ($/kWh)	Comment/source
Saint Martin's island, Bangladesh	0.57	This study
Coastal areas of Bangladesh	0.31-0.51	(Khadem, 2006)
Remote locations of India	0.10-1.86	(Nouni et al., 2007)
Six different cities of Nigeria	0.129-0.327	(Ajayi et al., 2014)
Six different cities of Nigeria	0.0238-7.72	(Ohunakin et al., 2013)
Five different places in Turkey	0.09-0.78	Five different capacities of wind turbine were considered (Genc, 2010)

3.2 Environmental impact assessment

The renewable energy sources are thought of clean sources of power generation only if greenhouse (GHG) gas mitigation potential is calculated based on the operational phase without considering the upstream stages (i.e. raw material extraction, manufacturing and transportation). This study accounts for GHG emissions from cradle-to-grave life cycle. Life cycle analysis has become a very popular tool to quantify the emissions of GHGs from all the unit operations (e.g. extraction, transportation, end use, etc.) of a product or system (Md Mustafizur Rahman, Canter, & Kumar, 2014, 2015). A wind turbine power plant emits only 9 g-CO_2 per kWh of electricity produced (Guezuraga, Zauner, & Pölz, 2012) on a life cycle basis. The grid emission factor of Bangladesh is 637 g-CO_2/kWh (Brander, Sood, Wylie, Haughton, & Lovell, 2011). Wind turbine plants have a significant potential to reduce GHGs. This study shows how much GHGs can be reduced if conventional power generation systems are replaced by wind power plants. Table 7 shows the emission factors (EFs) of different electricity generation techniques. The wind turbine system produces 18.07 MWh/year of electricity which emits only 162.63 kg-CO_2/year (there is no operational emissions). With the Bangladeshi national grid emission factor of 637 g-CO_2/kWh, the wind power plant can mitigate 11,347.96 kg-CO_2/year if the national grid mix is replaced by wind power generation system. The CO_2 mitigation potential of a wind power plant are 8745.88 kg-CO_2/year, 18,738.59 kg-CO_2/year and 17,473.69 kg-CO_2/year if a wind power plant replaces a gas, coal and oil power plant, respectively. It is not feasible to replace all the conventional power plants with the renewable power plants due to cost and resource availability constraints. But GHG emissions can be reduced significantly by incorporating more renewable based power generation systems in the country's total power generation capacity.

Table 7
Emission factors of different power generation system

Power generation system	Emission factor (g-CO_2/kWh)	Comment/source
Wind turbine	9	(Guezuraga et al., 2012)
Bangladeshi grid	637	(Brander et al., 2011)
Coal power plant	1046	(Guezuraga et al., 2012)
Gas power plant	493	Combined cycle power plant (Ramachandran Kannan, Leong, Osman, Ho, & Tso, 2005)
Oil power plant	976	(R Kannan, Tso, Osman, & Ho, 2004)

3.3 Sensitivity analysis

Sensitivity analysis was performed to observe the impact of different variables on the final results. In this study, seven parameters- interest rate, costs of turbine, battery bank and inverter, lifetime of turbine, battery bank and inverter were varied by ±20 to see the impact on the COE. The base-case numbers of these parameters are presented in Table 4. Figure 9 shows the results of the sensitivity analysis. The COE ($/kWh) increases with the increase in the capital cost of wind turbines ($/kW). This parameter has the largest influence on the COE (see Figure 9). A 20% increase in the interest rate increases the COE by 9.79% because the increased discount rate increases the total cost of the project. The cost of electricity is changed from $0.54/kWh to $0.60/kWh when the battery bank cost varies to +20% from -20%. The impact of cost of inverter on the COE is negligible as the inverter is the least costly equipment in the system. On the other hand the increased lifetime reduces the COE of the system. The shift in the lifetime of battery bank from 5 years to 6 years results in a $0.02 reduction in the COE. The lifetime of the turbine has the similar impact on the COE (see Figure 9).

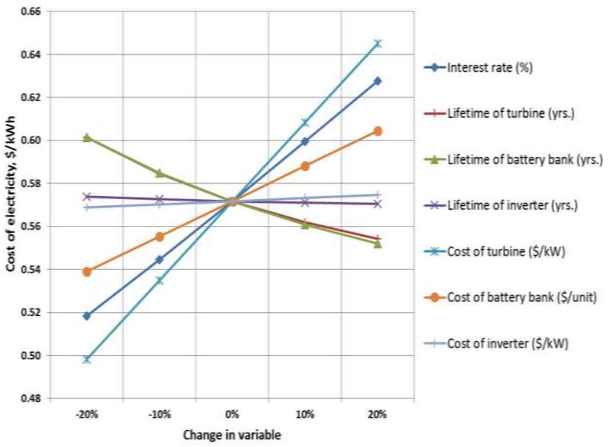

Figure 9 Sensitivity analysis for COE

4. Conclusions

The current study estimates the COE for an isolated remote community in the coastal area of Bangladesh through the development of an excel-based techno-economic model. The model estimates the COE as $0.57/kWh or BDT 44.02/kWh with a capital cost of $63,550.16 or BDT 4,893,362.22. The model also shows that wind turbine is the most costly equipment of the power generation system followed by the battery bank. This study reveals that electricity can be produced at a lower cost with wind energy than diesel generator for the selected location. The electricity generation from wind is not only cost competitive but also environmentally friendly. The proposed electricity generation system from wind could mitigate 17,473.69 kg-CO_2/year if diesel generator power generation system is replaced by wind power generation system. An analysis was performed to understand the influence of different input parameters on the final results. The sensitivity analysis reveals that the turbine cost is the most dominating factor on the COE. This study will help the government and other policy makers to replace the off-grid diesel generation systems with the wind turbines where there is sufficient wind speed for power generation. The present study will also be helpful for comparing the economics of different renewable power generation technologies.

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