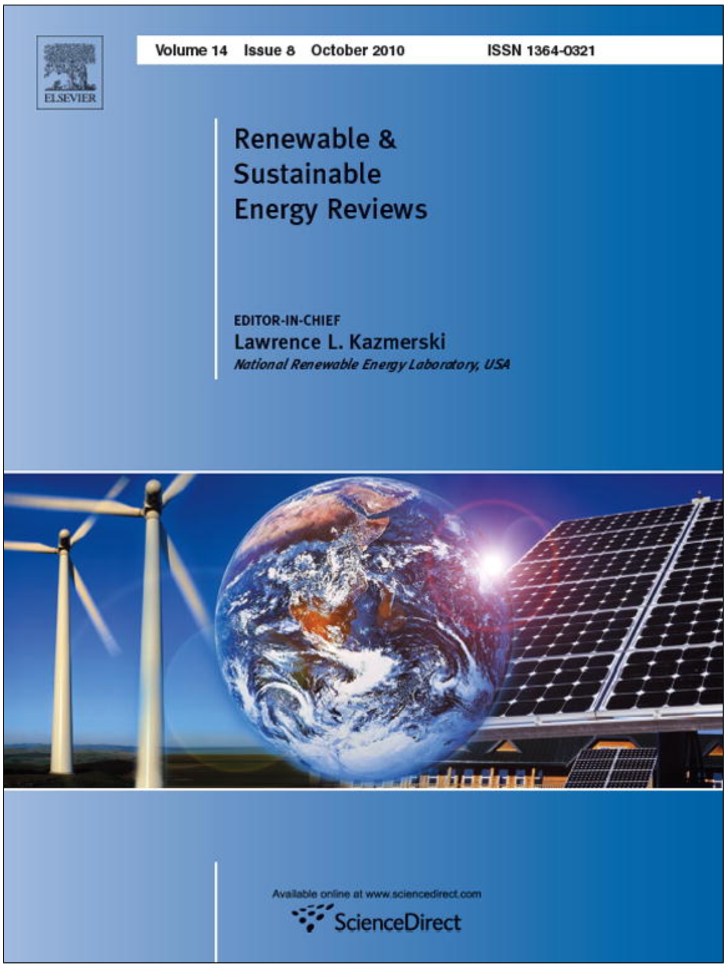
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Assessment of renewable energy resources potential for electricity generation in Bangladesh

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A B S T R A C T

Renewable energy encompasses a broad range of energy resources. Bangladesh is known to have a good potential for renewable energy, but so far no systematic study has been done to quantify this potential for power generation. This paper estimates the potential of renewable energy resources for power generation in Bangladesh from the viewpoint of different promising available technologies. Estimation of the potential of solar energy in Bangladesh is done using a GIS-based GeoSpatial Toolkit (GsT), Hybrid System Optimization Model for Electric Renewables (HOMER) model and NASA Surface Meteorology and Solar Energy (SSE) solar radiation data. The potential of wind energy is estimated by developing a Bangladesh wind map using NASA SSE wind data and HOMER model. A review of country's biomass and hydro potential for electricity generation is presented. The technical potential of gird-connected solar PV is estimated at 50,174 MW. Assuming that 1000 h per year of full power is the feasible threshold for the exploitation of wind energy, the areas that satisfy this condition in the country would be sufficient for the installation of 4614 MW of wind power. The potential of biomass-based and small hydro power plants is estimated at 566 and 125 MW, respectively. The renewable energy resources cannot serve as alternative to conventional energy resources, yet they may serve to supplement the long-term energy needs of Bangladesh to a significant level.

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1. Introduction

1.1. Energy and environment

The measure of development in any society of today is synonymous with the level of energy consumption. Energy is therefore recognized as a critical input parameter for national economic development. Modern day energy demands are still met largely from fossil fuels such as coal, oil and natural gas. In 1980, the global primary energy demand was only 7228 million ton of oil equivalent (mtoe) but this had increased to 11,429 mtoe by 2005 [1]. Further increases can be expected, mostly in connection with increasing industrialization and demand in less developed countries, aggravated by gross inefficiencies in all countries. Fossil fuels provide energy in a cheap and concentrated form, and as a result they dominate the energy supply. In total energy demand, the share of fossil energy is around 80%, while the remaining 20% are supplied by nuclear and renewable energy [2]. In 2005, a total of 26.6 billion tons of CO_2 emissions were generated world-wide of which more than 41% was from power generation based on fossil fuels [1]. The CO_2 emissions from power generation are projected to increase 46% by 2030. In 1980, total global electricity generation was 8027 TWh, which had increased to 17,363 TWh by 2005. The installed capacity of power generation was 1945 GW in 1980 and had increased to 3878 GW by 2005 [3] of which almost 69% was from conventional fuels. The main problem is that in the next 20 years the expected demand for electricity would require the installation of the same power generation capacity that was installed over the entire 20th century. This translates to the stunning number of one 1000-MW power station installed every 3.5 days over the next 20 years [4].

The concentration of greenhouse gases (GHGs) in the atmosphere has been increasing for a variety of reasons. CO_2 in the atmosphere is increasing as a result of the burning of fossil fuels. Global warming and mitigation of GHGs are presently the major issues of international concern. The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 to study different aspects of climate change. One aspect is the progressive gradual rise of the earth's average surface temperature, thought to be caused in part by increased concentrations of GHGs in the atmosphere. This so-called global warming is commonly described as climate change, although it is only one of the changes that affect the global climate. The major key findings of IPCC 4th assessment report are [1,5–6]:

1) Most of the observed increase in globally averaged temperatures since the mid 20th century is very likely due to the observed increase in anthropogenic GHG concentration. Discernable human influences now extend to other aspects of climate, including ocean warming, continental average temperature and temperature extremes.
2) For the next two decades, a warming of about 0.2 °C per decade is projected for a range of emission scenarios. Even if the concentrations of all GHGs were to be kept constant at the year 2000 levels, a further warming of about 0.1 °C per decade would be expected.
3) Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if the levels of GHG concentrations were not to change.

1.2. Energy and sustainable development

Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs [7]. Energy development is increasingly dominated by major global concerns of air pollution, fresh water pollution, coastal pollution, deforestation, biodiversity loss and global climate deterioration. To prevent disastrous global consequences, it would increasingly be impossible to engage in large-scale energy-related activities without insuring their sustainability, even for developing countries in which there is a perceived priority of energy development and use and electricity generation over their impact on the environment, society, and indeed on the energy resources themselves. The long-term control of global climate change and holding it at a safety levels requires a connection of policies for climate change to sustainable development strategies in all nations. Over the last few decades, a decline in fossil fuels reserves has been observed world-wide. Alternately, fossil fuels are not being newly formed at any significant rate, and thus present stocks are ultimately finite. If the current rate of energy consumption is continued, the limited reserves of coal, oil and natural gas may last only for 122, 42 and 60 years, respectively [4,8]. The amount of uranium in the world is insufficient for massive long-term deployment of nuclear power generation [4]. Therefore, the sustainable development issue is more than ever raised, stimulating the need to search for a sustainable development path.

There are two paths to provide energy services to the people [9]:

1) The hard path or unsustainable path continues with heavy reliance on unsustainable fossil fuels or nuclear power. This

leads to serious pollution problems and disposal of radioactive waste problems.
2) The soft or sustainable path relies on energy efficiency and renewable resources to meet the energy requirement.

National energy planning with an emphasis on renewable resources and improvement of energy efficiency contributes to sustainable development. Currently, the centralized planning approach is adopted for resource management and energy policy decisions. There is a need to move towards the softer path to ensure sustainable development for the present and the future. This is the path to increase reliance on clean renewable energy resources and improved energy use efficiency and conversion measures to minimize the loss of primary resources without the risk of climate or ecology breakdown. Consequently, almost all national energy policies include some of the following vital factors for improving or maintaining social benefits from energy [7]:

1) Increased harnessing of renewable supplies
2) Increased efficiency of supply and end-use
3) Reduction in pollution.

1.3. Energy situation in Bangladesh

Electricity is a pre-requisite for the technological development and economic growth of a nation. The future economic development of Bangladesh is likely to result in a rapid growth in the demand for energy with accompanying shortages and problems. The country has been facing a severe power crisis for about a decade. Known reserves (e.g., natural gas and coal) of commercial primary energy sources in Bangladesh are limited in comparison to the development needs of the country [10]. Power generation in the country is almost entirely dependent on fossil fuels, mainly natural gas, that accounted for 81.4% of the total installed electricity generation capacity (5248 MW) in 2006 [11]. By that year, only about 42% of total population had been connected to electricity [12], with vast majority being deprived of a power supply. The government of Bangladesh has declared that it aims to provide electricity for all by the year 2020, although at present there is high-unsatisfied demand for energy, which is growing by more than 8% annually [13]. Demand-supply gaps and load shedding have increased (Fig. 1).

Coal is expected to be the main fuel for electricity generation. The government of Bangladesh has planned to generate 2900 MW power from coal in the next 5 years [14], although coal power has adverse environmental effects and coal reserves are limited. The government has also focused on furnace-oil-based peaking power plants. As a result, the share of CO_2 emissions coming from fossil-fuel-based power plants in the national CO_2 inventory is expected to grow, and there is a growing dependency on imported fossil fuels for power generation.

Increasing the use of fossil fuels to meet the growing world-wide electricity demand, especially in developing countries, not only counteracts the need to prevent climate change globally but also has negative environmental effects locally. In Bangladesh, the power sector alone contributes 40% to the total CO_2 emissions [15–16]. In this case, it is necessary to develop and promote alternative energy sources that ensure energy security without increasing environmental impacts.

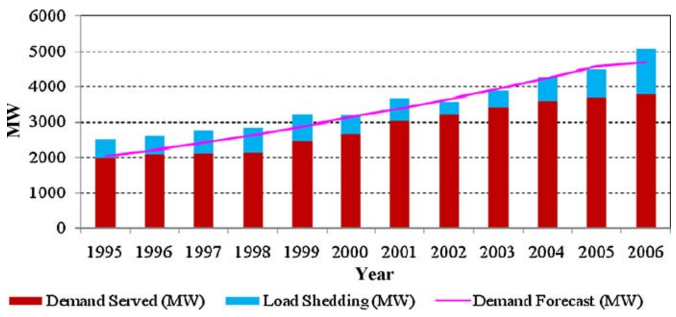

Fig. 1. Power demand-supply gaps and load shedding in Bangladesh [11].

Bangladesh is facing daunting energy challenges: security concerns over growing fuel imports, limited domestic energy resources for power generation, and projected demands for electricity that will exceed domestic supply capabilities within a few years.

By acknowledging the potential of renewable energy resources, the country could possibly meet its unprecedented energy demand, thus increasing electricity accessibility to all and enhancing energy security through their advancement. The integration of renewable energy technologies in the power sector through national energy planning would be, therefore, the right direction, not only for sustainable development of the country but also as the responsibility of Bangladesh toward the global common task of environmental protection.

The government target is to generate 5% total electricity using renewable energy technologies by 2015 and 10% by 2020 [17]. The use of solar, biomass, hydro and wind energy technologies is expected to play a major part in meeting this target.

1.4. The present study

In this study, the potential of renewable energy resources for electricity generation in Bangladesh is estimated from the viewpoint of different promising available technologies. This paper describes different renewable energy technologies and future prospects of all selected technologies for power generation. It also develops a wind map of Bangladesh.

2. Selection of renewable energy forms and the technologies

Whereas fossil energy sources are fixed in stock, renewable energy sources are not limited, but usually are not in ready-to-use forms for power generation. To convert renewable energy into electricity, energy-converting systems are needed. Therefore, the potential renewable energy is dependent on the technical ability of this conversion system. There are many technologies that can be used to harvest renewable energy, but not all of them appear promising. Based on the availability of renewable energy sources, specific conditions, and the technology level in Bangladesh, the present study focuses on renewable energy sources for which commercial technologies exist for power generation (Table 1).

2.1. Selected renewable energy and related technologies

2.1.1. Solar energy

The energy from sunlight reaching the earth is a huge potential that can be exploited and used for generating electricity. Among several available technologies, solar photovoltaic (PV) is the most

Table 1
Selected renewable energy technologies.

Renewable resource	Technology
Solar	Solar home system (SHS)
	Hybrid system
	Grid-connected solar photovoltaic (PV)
Wind	Grid-connected wind turbine
Biomass	Direct combustion
	Gasification
Hydro	Large hydro
	Small hydro

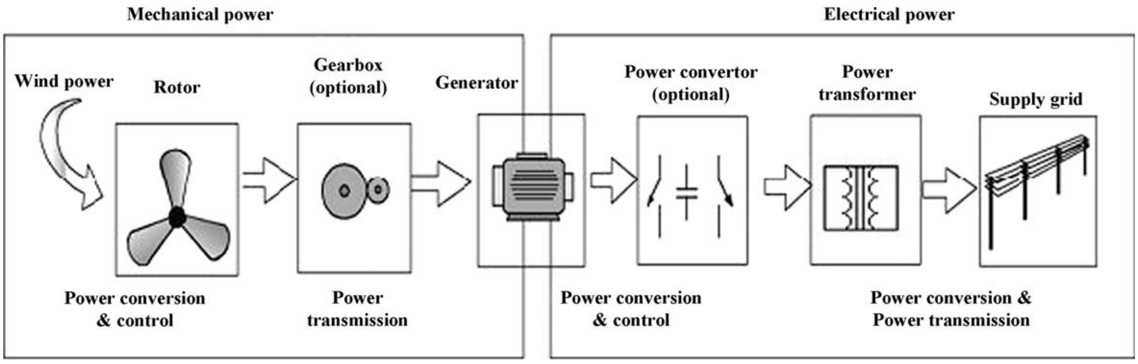

Fig. 2. Main components of wind turbine system [29].

promising. PV technology converts sunlight into direct current (DC) electricity. When light falls on the active surface of the solar cell, electrons become energized and a potential difference is established, which drives a current through an external load. The central issue with PV technology is cost. The unit cost of PV has sunk in several orders of magnitude while the efficiency is continuously being improved [18–22]. Solar PV is becoming more and more popular owing to high modularity, no requirement for additional resource (e.g., water and fuel), no moving parts and low maintenance required.

Over the last two decades, the cost of manufacturing and installing solar PV system has decreased by about 20% for every doubling of installed capacity [18]. The solar industry has grown at a rate of 30% per annum over the last five years [20].

2.1.1.1. Grid-connected solar PV system. Different types of grid-interactive systems are being tested in countries where extensive utility grid lines are available. A PV array is connected and synchronized to the grid using an appropriate power conditioning sub-system that converts the DC energy to alternating current (AC) energy synchronized to the grid energy [23]. Therefore, no additional energy storage is necessary. The grid itself is the storage medium for such a grid-interactive system, which delivers energy to the grid as long as enough sunshine is available. The system is usually integrated directly into structural elements of buildings (roof, façade). Therefore, the system has the following advantages [24]

1) It reduces both energy and capacity losses in the utility distribution network, as the electric generators are located at or near the site of the electrical load.
2) It avoids or delays upgrades to the transmission and distribution (T&D) network where the average daily output of the PV system corresponds with the utility's peak demand period (afternoon peak demand during summer as a result of loads from cooling).
3) It is cost competitive, since the savings for building material is considered, i.e., no roof tiles are needed when solar panels are installed.

In recent years, rapid development in grid-connected building-integrated PV systems is due to the government-initiated renewable energy programs aiming at the development of renewable energy applications and reduction of greenhouse gas emissions. This type of solar PV system is preferred as far as PV installations are concerned. Germany introduced a "100,000 roofs program" [25]. The Japanese 70,000 roofs program started in 1994 and dominated the market for the rest of the 1990s [18]. A PV system dissemination program has been very successful in USA, and its 1 million solar-roof initiative is going well [26]. Grid-connected PV systems thus took off in the mid-to-late 1990s and since then have been the dominant application [18].

2.1.1.2. Solar home system (SHS). The system consists of a 20–100 watt peak (Wp) PV array,[1] a rechargeable battery and a charge controller. Both the array size and sunlight availability determine the amount of electricity available for daily use [27]. With an appropriate sunlight regime, the system has proven to be competitive for remote households. The SHS is thus implemented in many developing countries. In Bangladesh, by the end of 2008 a total of about 350,000 SHSs had been installed [28].

2.1.1.3. Hybrid system. When renewable energy technologies are used in decentralized and remote areas, they can be coupled with diesel generators to improve the total system reliability. Wind-diesel generator-battery, wind-solar PV-diesel generator-battery, PV-diesel generator-battery hybrid can be used for generating electricity in the rural areas of Bangladesh.

2.1.2. Wind energy

The energy from continuously blowing wind can be captured using wind turbines that convert kinetic energy from wind into mechanical energy and then into electrical energy (Fig. 2). Electricity generated by wind turbines can feed to the central grid or be locally consumed using small stand-alone wind turbines.

2.1.2.1. Grid-connected system. Two types of grid-connected systems can be distinguished. In the first type, the system's main priority is to cater for the local electricity demand, and any surplus generation will be fed to the grid. When there is a shortage, electricity is drawn from the grid. The other option is the utility scale, where decentralized stations are managed by the utilities in the same way as large electric power plants. Some of the important features of the grid systems are as follow [30]

1) A grid-connected system is an independent decentralized power system
2) The operational capacity is determined by the supply source
3) Due to supply-driven operation, the system may have to ignore the local demand when the supply source is not available
4) The system can be either used to meet the local demand and surplus can be fed to the grid, or may exist only to feed the grid
5) The connectivity to a grid enables setting up relatively large-scale turbines.

[1] The capacity of a PV module is defined in terms of peak of output (in watts (Wp)). The rated peak output is measured under standard test conditions of 1000 W/m^2 solar radiation, and 25 °C cell temperature. SHSs are often designed to be smaller than 20 Wp and larger than 100 Wp.

Table 2
Average daily solar radiation at 14 locations in Bangladesh [35,36].

Station name	Elevation (m)	Latitude (degrees)	Longitude (degrees)	Radiation (RERC)[a] (kWh/m^2/day)	Radiation (NASA) (kWh/m^2/day)
Dhaka	50	23.7	90.4	4.73	4.65
Rajshahi	56	24.4	88.6	5.00	4.87
Sylhet	225	24.9	91.9	4.54	4.57
Khulna	11	22.8	89.6	–	4.55
Rangpur	230	25.7	89.3	–	4.86
Cox's Bazar	76	21.4	92	–	4.77
Dinajpur	194	25.6	88.6	–	4.99
Kaptai	345	22.5	92.2	–	4.71
Chitagong	118	22.3	91.8	–	4.55
Bogra	59	24.8	89.4	4.85	4.74
Barisal	31	22.7	90.4	4.71	4.51
Jessore	23	23.2	89.2	4.85	4.67
Mymensingh	114	24.8	90.4	–	4.64
Sherpur	308	25	90	–	4.67

[a] Data from RERC, Dhaka University, Bangladesh.

Suitable grid-connected wind systems need to satisfy several geographical and technical conditions, e.g., high average annual wind speed, easy access to the power distribution grid, and low turbulence. Wind turbines for grid-connected systems are the most highly demanded on the market and increased by 30% per annum between 1998 and 2008 [8]. The technology of these turbines and grid systems are becoming increasingly well developed and their cost has dropped significantly [31].

2.1.3. Biomass

Biomass covers all kinds of organic matters from fuel wood to marine vegetation. Biomass is the fourth largest source of energy world-wide and provides basic energy requirements for cooking and heating of rural households in developing countries.

Energy generation using biomass offers a promising solution to environmental problems by reducing the emission of common greenhouse gases. A wide range of options exists for conversion of biomass into energy such as heat energy and electrical energy. Two widespread technologies are direct combustion and gasification.

Direct combustion involves the oxidation of biomass with excess air, producing hot flue gases which in turn produce steam, which is used to generate electricity. In a condensing steam cycle only electricity is produced, while in an extracting steam cycle both electricity and steam are generated [32].

Gasification involves conversion of biomass to produce a medium- or low-calorific gas. The gained gas is then used as fuel in combined cycle power generation plants. Being produced in a combined cycle power plants, electricity from this technology has higher efficiency and is more competitive than that from a steam turbine.

Biogas is a mixture of CH_4 (40–70%), CO_2 (30–60%) and other gases (1–5%) produced from animal dung, poultry droppings and other biomass wastes in specialized bio-digesters [33]. This gas is combustible and can be used to generate electricity.

2.1.4. Hydro energy

Kinetic energy from flowing or falling water is exploited in hydropower plants to generate electricity. Hydropower plants are divided into two categories: (1) Large hydropower plants (>10 MW), usually with reservoirs, that can not only produce electrical energy continuously but also are able to adjust their output according to electricity demand and (2) small hydropower plants (<10 MW) that are less flexible with respect to load or demand fluctuation due to their dependence on the water resource. Hydropower technologies are mature and widely available.

3. Assessment of renewable energy potential in Bangladesh

3.1. Definition of energy potentials

Renewable energy potentials are classified into different categories, namely theoretical potential, available potential, technical potential and economic potential [34].

- Theoretical potential refers to the total energy available for extraction in a defined region without consideration of technical restrictions. Therefore, due to energy forms, such as solar and wind energy, the theoretical potential is huge.
- Available potential refers to the part of the theoretical potential that can be harvested easily without causing impacts on the environment.
- Technical potential refers to the amount of energy that can be exploited using existing technologies and thus depends on the time point of assessment.
- Economic potential refers to the amount of potential energy that is economically viable by currently given technologies. Infrastructure or technical constraints and economic aspects define the limits for the economic potential. Therefore, the economic potential depends on the costs of alternative or competing energy sources.

3.2. Solar energy resource potential

Bangladesh is situated between 20.30° and 26.38° north latitude and 88.04° and 92.44° east longitude with an area of 147,500 km^2, which is an ideal location for solar energy utilization. Estimation of the potential of solar energy in Bangladesh is done using a GIS-based GeoSpatial Toolkit (GsT) and NASA Surface Meteorology and Solar Energy (SSE) solar radiation data. GsT is one of the tools of the Solar and Wind Energy Resources Assessment (SWERA) application developed by the United Nations Environmental Program (UNEP) project funded by the Global Environmental Facility (GEF). Due to the limited solar radiation data in Bangladesh, a NASA SSE data set for the period from July 1983 to June 1993 was used and compared to the measured data from the Renewable Energy Research Center (RERC), Dhaka University, for six different stations in Bangladesh (Table 2). The data vary from 0.66% to a maximum 4.52% from the NASA SSE data set at the same locations.

The theoretical potential of the solar resource is estimated based on the availability of data on solar irradiation and land area. The theoretical potential is then converted into technical potential by introducing social and technical constraints. Social constraints mainly concern the identification of suitable locations for installation of solar energy technologies. Technical constraints

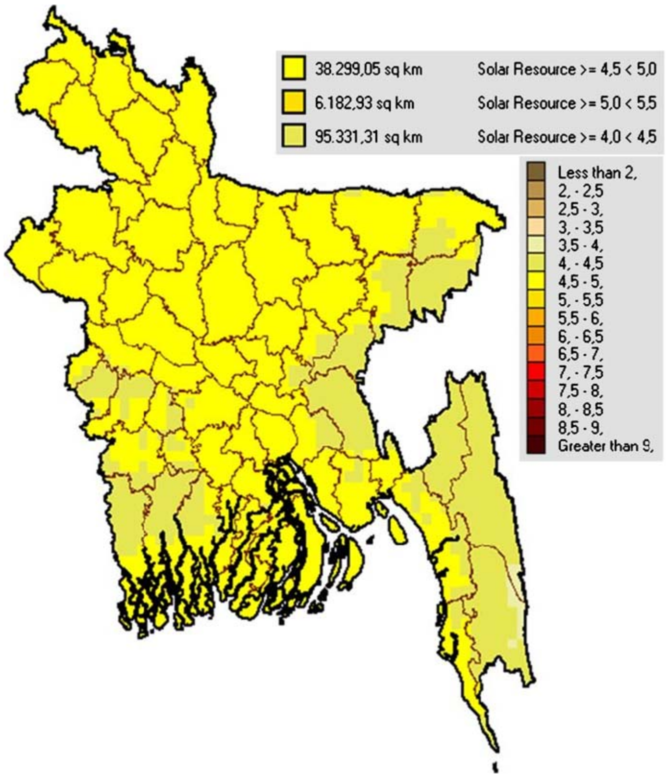

Fig. 3. Solar radiation (kWh/m^2/day) and area of Bangladesh with highest potential for solar energy utilization.

concern the characterization of exploitation technologies and the organizational setting conditions that have to be satisfied in the implementation of renewable energy technology projects.

3.2.1. Theoretical potential

The GeoSpatial Toolkit provides the solar map of Bangladesh and it shows that the solar radiation is in the range of 4–5 kWh/m^2/day on about 94% of Bangladesh (Fig. 3). Data on average sunny hours per day (Fig. 4) and monthly solar radiation (Fig. 5) were taken from NASA SSE for 14 widely distributed locations in Bangladesh using the Hybrid System Optimization Model for Electric Renewables (HOMER) software. The average sunny hours per day are 6.5, and the annual mean solar radiation is 0.2 kW/m^2. This indicates that Bangladesh theoretically receives approximately 69,751 TWh of solar energy every year, i.e., more than 3000 times higher than the current (2006) electricity generation in the country. However, in the course of exploitation, constraints such as land use, geographical area and climate are encountered. In addition, several of solar energy technologies are limited by different factors. For detailed information, it is therefore necessary to examine the potential of solar energy from the viewpoint of a specific application.

3.2.2. Technology selection

Different solar energy technologies are available on the world market. Three technologies that seem to be the most suitable for Bangladesh are grid-connected solar PV, SHSs and hybrid systems (solar, wind and diesel generator).

3.2.3. Technical potential

The average annual power density of solar radiation is typically in the range of 100–300 W/m^2. Thus, with a solar PV efficiency of 10%, an area of 3–10 km^2 is required to establish an average electricity output of 100 MW, which is about 10% of a large coal or nuclear power plant [22]. Unlike other energy conversion technologies, solar energy technologies cause neither noise, nor pollution; hence they are often installed near consumers to reduce construction costs. Thus, identification of suitable locations for application of solar energy is practically the search for suitable rooftops and unused land. A study suggested that 6.8% (10,000 km^2) of Bangladesh's total land is necessary for power generation from solar PV to meet electricity demand of 3000 kWh/capita/year [37]. Another study found that total household roofs area is about 4670 km^2 [38] which is about 3.2% of total land area of the country. In urban area (Dhaka city) 7.86% of total land is suitable for solar PV electricity generation [39].

Considering the grid availability, only 1.7% of the land in Bangladesh is assumed technically suitable for generating electricity from solar PV [40]. The capacity of grid-connected solar PV is derived using the annual mean value of solar radiation (200 W/m^2) and a 10% efficiency of the solar PV system. Thus, the technical potential of grid-connected solar PV in Bangladesh is calculated as about 50,174 MW.

Whereas the potential market for grid-connected PV systems is in the densely populated urban and electrified areas, the potential market for SHSs is households without access to the national grid network, especially those in remote and mountainous areas. According to a survey report, a market of SHSs of approximately 0.5 million households reaching 4 million in the future is envisioned in Bangladesh [41]. Considering an average standard 50-Wp solar panel for each household [42], the technical total capacity will be equivalent to 200 MW. The same capacity is applicable for the hybrid system, as this system is suitable only for rural non-

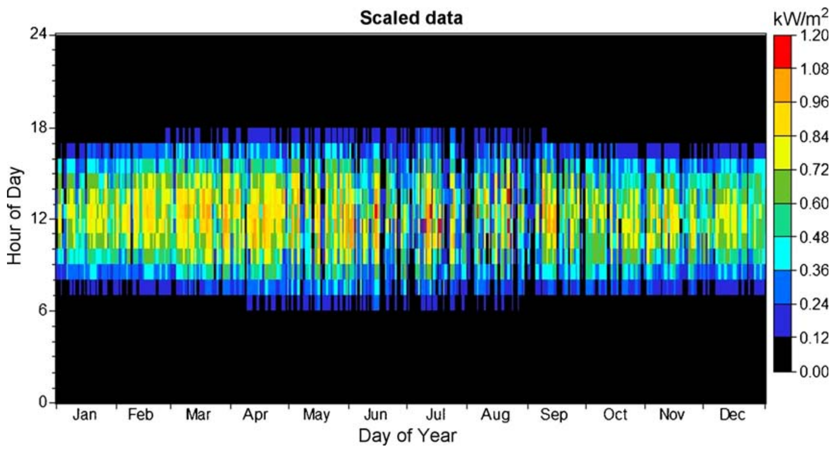

Fig. 4. Monthly average sunshine hours in Bangladesh.

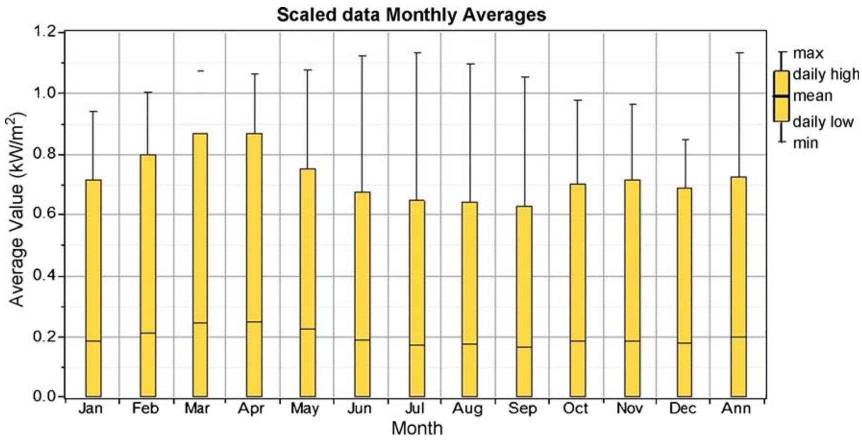

Fig. 5. Monthly average solar radiation in Bangladesh.

electrified remote areas. Economic viability of SHSs in Bangladesh was evaluated in [43] and techno-economic viability of hybrid systems was described in [44].

3.2.4. *Prospects for solar PV*

There are many factors that can make solar PV more competitive in the future:

3.2.4.1. Cost of solar PV. The development of the cost scenario of solar PV is very important as a parameter, as it determines its market penetration in developing countries like Bangladesh. Most products show a decrease in unit cost with increased manufacturing experience. The cost of PV decreased from several hundred US $/Wp in 1970 to about US $ 5–6/Wp in the mid 1990s [45]. In an idealized model, the costs progress as a constant learning curve. The prospects for solar PV are revealed when extrapolating the historical learning cost curve, which shows a learning rate of 20.2%. The recent funding initiatives on PV deployment will lead to an increase in experience, and this will likely lead to a significant drop in prices. At the current speed of market increase, it can be estimated that the price will drop about 20% every 4 years [19].

3.2.4.2. Efficiency. The current efficiency is far below the theoretical efficiency. This indicates sufficient room for the improvement of solar PV efficiency. A survey of the nominal efficiency of first generation commercial modules gave a range of 10–15% [20]. The efficiency of a crystalline silicon cell increased from 13% in 1976 to nearly 32% in 1992 [21]. During the same period, typical module efficiency rose from 7–8% to 10–13%. The present positive development of the industry is helping to stimulate the introduction of improved manufacturing techniques and technology. The second generation of solar PV, which is more competitive, is expected to appear over the coming decade [20].

3.2.4.3. Limited fossil resources and increasing prices. The depletion of fossil fuels is occurring at a fast rate due to the growing gap between the demand and production of fossil fuels [23]. At the same time, these fuels experience an opposite trend to that of solar PV, e.g., the price for produced electricity is increasing due to the increase in the price of fossil fuels and environmental costs, e.g. for CO_2 emissions.

3.3. *Wind energy resource potential*

3.3.1. *Technical potential of grid-connected wind turbines*

Assessment of the wind energy resource and the installation of wind energy conversion systems in Bangladesh have long been hindered due to lack of reliable wind speed data. There is no reported wind map of Bangladesh that could be relied upon and used for wind energy assessment [46]. One of the very first steps towards harnessing energy from the wind is to make an extensive assessment of the wind energy potential for electricity generation and a cost analysis for a site of interest.

First, the theoretical potential of wind energy is estimated by developing a Bangladesh wind map. This is possible using a reference wind turbine and available wind speed data. The technical potential is then assessed by introducing restrictions grouped as social and technical constraints. The definition of social constraints enable elimination of areas not suitable for the exploration of the wind energy potential such as high latitude, restricted and protected areas, and residential areas. Technical constraints define basic conditions for the operation of wind turbines such as arrangement of wind turbines and the minimum wind velocities [47]. In this study, a NASA SSE data set [36] is used to develop a wind map of Bangladesh to determine potential sites for wind energy exploration. Then a reference wind turbine is used to find the power density. Candidate sites are estimated based on the developed wind map. Finally, constraints were applied for the technically potential area, which was converted to the total technical potential of wind energy for Bangladesh.

Unlike surface measurements, the NASA SSE data set consists of a 10-year global average on a 1° by 1° (about 100 km × 100 km) grid. The NASA SSE data, which are essentially an average over the entire area of the cell, may not represent a particular site within the grid. However, this database is an excellent and easy to use source, which could be used for any preliminary study for renewable energy resource estimation [46,48].

One set of wind speed data for 50 m height was gathered for 20.5–26.5°N and 78.5–92.5°E. Based on these data, the Bangladesh wind map was developed for the theoretical potential (Fig. 6). The only coastal regions appear as high wind areas when compared with the main land.

3.3.2. *Selection of wind turbine*

To find the technical potential of wind energy it is necessary to have a reference wind turbine so that a theoretical power output corresponding to each wind speed value can be calculated. This wind turbine should suit the local conditions, including the local possibility of manufacturing accessories. Furthermore, road conditions, the availability of suitable mobile cranes or trucks are the other important factors that also should be paid attention to [47].

Considering the above requirements, a wind turbine of 330 kW from Enercon (E33) was selected (Table 3). From the power curve (Fig. 7), it can be observed that E33 starts operation at a cut-in wind speed of 3 m/s. Beyond 13 m/s rated power, output remains constant. Cut-out wind speeds are those higher than 25 m/s.

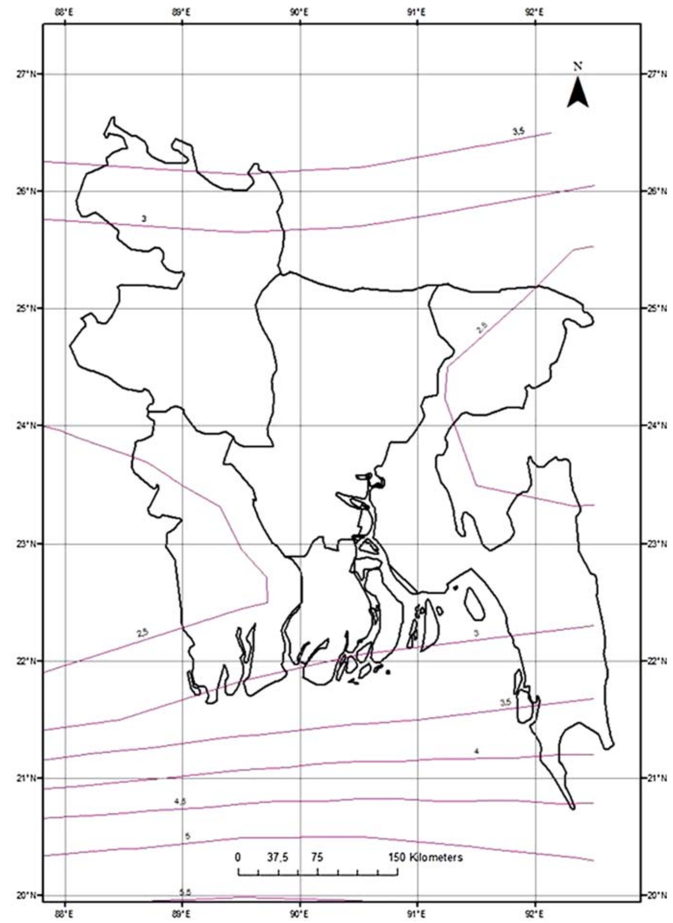

Fig. 6. Wind map of Bangladesh at 50 m height using NASA SSE data set (m/s).

3.3.2.1. *Calculation of energy output.* The HOMER optimization tool was used to find the total energy output of the wind turbine. The Weibull distribution function is mostly used to represent the distribution of wind. HOMER uses the distribution function as

$$f(v) = \left(\frac{C}{A}\right)\left(\frac{V}{A}\right)^{c-1} \times \exp\left(-\left(\frac{V}{A}\right)^{c}\right) \quad (1)$$

where $f(v)$ = Weibull probability function for wind speed v, C = shape parameter, which typically ranges from 1 to 3 [50]. For a given average wind speed, the higher the shape parameter is, the narrower the distribution of wind speed around the average value. Because the wind power varies with the cube of the wind speed, a lower shape parameter normally leads to higher energy production at a given wind speed. A = scaling parameter. When C equal to 2, the Reyleigh function represents well enough the real wind speed distribution and it is then possible to derive the wind speed distribution if only yearly average wind speed is known. In HOMER, C equal to 2 and yearly average wind speed are used.

Table 3
Specification of E33.

Technical parameter	Value
Rotor diameter	33.4 m
Swept area	876 m^2
Rated power	330 kW
Starting wind speed	3
Rated wind speed	12 m/s
Cut-out wind speed	28–34 m/s
Generator	Synchronous
Number of blades	3
Tower height	50 m

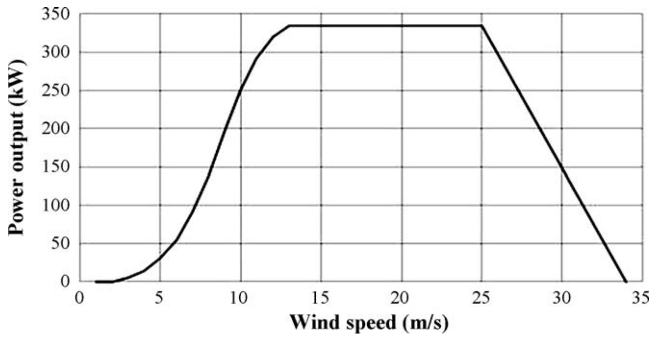

Fig. 7. Power curve of E33–330 kW wind turbine [49].

Finally, HOMER calculates yearly energy production applying logarithmic or power low profile with standard temperature and pressure, and air density. With the distribution function and power curve, the yearly energy production (YEP) is calculated by HOMER by integrating the power output at every bin width using the following equation:

$$YEP(v_m) = \sum_{v=1}^{v=25} f(v) \times P(v) \times 8760 \quad (2)$$

where v_m = average wind speed, $P(v)$ = turbine power at wind speed v, $f(v)$ = Weibull probability function for wind speed v, calculated for the average wind speed v_m.

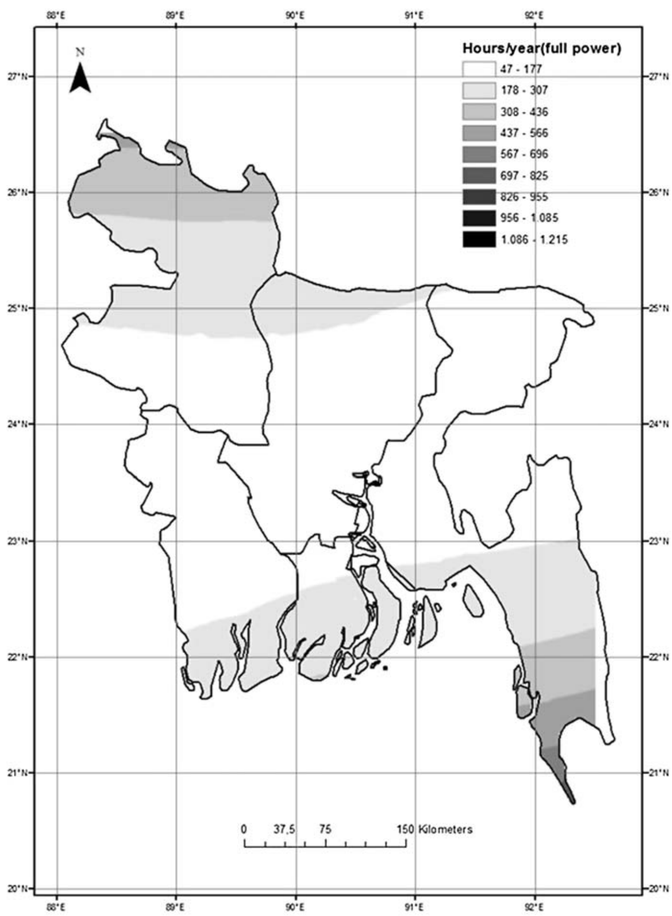

Fig. 8. Theoretical potential of wind energy in Bangladesh.

To calculate the hours per year with full power, the energy production is divided by reference turbine rated power. The theoretical potential of wind energy output for Bangladesh in the form of hours with full power is relatively high in only coastal regions (Fig. 8).

3.3.3. Technical potential

For an infinite number of wind turbines with 10 rotor diameters (10D) spacing, the limited array efficiency is about 60%. For a finite number, average losses are much lower, and closer sitting is more practical [51]. For the case of the Bangladesh coastal area, finite or limited numbers of turbines are applicable. For simplicity, the present study takes 4D as the standard distance between two wind turbines. Thus, the area requirement for each E33 turbine will be 14,016 m^2 and as a result, wind turbine density will be 23.5 MW/km^2.

Assuming that 1000 h of full power (Fig. 8) is the feasible threshold for the exploitation of wind energy, the areas that satisfy this condition in Bangladesh would be sufficient for the installation of 4614 MW of wind power.

Due to limited wind resource potential, which is only in the coastal regions, stand-alone wind turbines are not considered in this study.

3.3.4. Future prospects for wind energy

In 2002, over 32 GW and in 2008 over 122 GW of wind capacity were installed world-wide [8,52]. Although wind energy currently represents about 0.1% of total electricity [53], it has the fastest relative growth rate of any electricity generating technology. Along with the increasing exploitation of wind energy, the cost of wind turbines dropped dramatically by 52% between 1982 and 1997 [31]. The Danish energy agency predicts that a further cost reduction of 50% can be achieved by 2020 [54]. Therefore, with increasing energy costs for conventional technologies and increasing environmental costs, wind power is becoming more and more attractive.

3.4. Biomass potential

Biomass energy is mainly from fuel wood, agricultural residues, animal dung and municipal solid wastes (MSW), the availability of which is linked with forestry resources, crop production, animal numbers and urban waste production. First, total biomass production is estimated and then the energy potential is estimated by applying the individual recovery rate, residue to yield ratio (for agricultural residues only), moisture content and calorific value.

Table 4
Annual agricultural crop production in 2003 [59].

Crop	Annual production (kton)
Rice	39090
Sugarcane	6838
Vegetables (total)	1837
Wheat	1507
Jute	792
Pulse	345
Coconut	88
Millet	57
Groundnut	45
Maize	10

3.4.1. Agricultural residues

Approximate land use for agriculture is 55% of the total land area of Bangladesh [35]. Agricultural residues from major crop residues such as straw and husks from rice plants, bagasse from sugarcane and jute tick contribute significantly to the biomass sector. There are two types of agricultural crop residues: field residues and process residues. Field residues are residues that are left in the field after harvesting and generally used as fertilizer. Process residues are generated during crop processing and are available at a central location.

Studies in neighboring Asian countries [55–58] produced useful residue to yield ratios for several agricultural crops. These ratios are used in this study together with published productivity figures for the individual crops (Table 4). It has been considered that only 35% of field crop residues can be removed without adverse effects on the future yields. Crop processing residues, on the other hand, have a 100% recovery factor [59]. In this study, only process agricultural residues are considered, as field residues are used for other purposes (Table 5). It is estimated that the total annual amount of recoverable agricultural crop residues is 44,104 kilo tons (kton), of which 60% are field residues and the remaining are process residues.

Table 5
Production and recoverable amounts of agricultural residues in 2003.

Crop residues	Residues production ratio	Residues generation (kton)	Residues recovery (kton)
Field residues			
Rice straw	1.695	66258	23190
Wheat straw	1.75	2637	923
Sugarcane tops	0.3	2051	718
Jute stalks	3	2376	832
Maize stalks	2	20	7
Millet stalks	1.75	100	35
Groundnut straw	2.3	78	27
Cotton stalks	2.755	124	43
Residues from vegetables	0.4	735	257
Residues from pulses	1.9	656	229
Subtotal		75035	26261
Process residues			
Rice husk	0.321	12548	12548
Rice bran	0.83	3244	3244
Sugarcane bagasse	0.29	1983	1983
Coconut shells	0.12	11	11
Coconut husks	0.41	36	36
Maize cob	0.273	3	3
Maize husks	0.2	2	2
Groundnut husks	0.477	16	16
Subtotal		17843	17843
Total		92877	44104

Table 6
Number of livestock and their residues [33,35].

Livestock	Number of heads (thousand)	Dung yield (kg/head/day)	Residues (mton/year)
Buffaloes	828	8–12	3.02
Cattle	23652	5–10	64.74
Goats	33800	0.25–0.50	4.62
Sheep	1121	0.25–0.50	0.15
Poultry chickens	200000	0.10	7.3
Total			79.84

3.4.2. Wood fuel

Total wood fuel supply and consumption in Bangladesh were 8999 and 9396 kton, respectively, in 2004 [60]. 1428 kton (15%) wood fuel comes from deforestation. Domestic cooking uses 63%, and the rest goes to industry and the commercial sectors [61]. Most of the fuel wood consumed by rural households is supplied by the homestead trees, and mainly consists of firewood, twigs and leaves. Estimates for the rate of supply of tree residues in recent years are not available. Total tree residues in 1992 were 1821 kton [59]. Both wood processing residues and recycled wood are an important source of energy. In 1998, 118 kton of sawdust was available for energy purposes [62]. Considering the 100% recovery rate and the unchanging production rate, the annual amount of recoverable biomass from forests and the forestry industry in Bangladesh is about 10,938 kton. On the other hand, FAO (1997) found that the future projection of demand and supply of wood fuel is bleak [60]. For this reason, in this study wood fuel is not considered for power generation.

3.4.3. Municipal solid waste (MSW)

Rapid urbanization and population growth are mainly responsible for the rapidly increasing rate of MSW generation in the urban areas of Bangladesh. The per capita waste generation and calorific value of various waste components are the most important data for calculating the potential of MSW to generate electricity. It has been found that in Dhaka city, the per day waste generation rate varies from 4000 to 5000 tons [63–65]. Different studies have found that per capita waste production in there ranges from 0.4 to 0.71 kg/day. In other large cities, it varies from 0.36 to 0.43 kg/day [66]. This is comparable to an average per capita MSW generation rate of 0.3 and 0.57 kg/day in two Indian cities namely Kanpur and Calcutta, respectively [23]. Due to a limited MSW in other cities for generating electricity, only four major cities are considered in this study. Based on the total population of the Dhaka, Chittagong, Rajshahi and Khulna city corporations and average waste generation per capita of 0.5 kg/day, a total of 8300 tons waste are generated daily. The average recovery rate of MSW is 70% [66], i.e., 2.12 million tons (mton) per year.

3.4.4. Animal waste and poultry droppings

Manure from cattle, goats, sheep and buffaloes are the common animal waste in the country. The quantity of waste produced per livestock per day varies depending on body size, type of feed and level of nutrition. The production rates are estimated by employing the number of heads of the national herds and the waste generation rate per head for the individual species (Table 6) [33]. The collection factor of animal waste and poultry droppings is considered to be 50% [59]. Accordingly, it is estimated that the total amount of recoverable animal and poultry waste in Bangladesh per year is about 40 mton.

3.4.5. Theoretical energy potential from recoverable biomass resources

The total annual recoverable rate of biomass in Bangladesh is about 126 mton per year (Table 7). Using the lower calorific values of the individual biomass components, the total available energy

Table 7
Energy potential of biomass resources.

Biomass	Recovery rate (kton/year)	Moisture content (% by mass)	Lower calorific value (GJ/ton)	Energy content (PJ)
Field residues				
Rice straw	23190	12.7	16.30	329.99
Wheat straw	923	7.5	15.76	13.46
Sugarcane tops	718	50	15.81	5.68
Jute stalks	832	9.5	16.91	12.73
Maize stalks	7	12	14.70	0.09
Millet stalks	35		12.38	0.43
Groundnut straw	27	12.1	17.58	0.42
Cotton stalks	43	12	16.40	0.62
Residues from vegetables	257	20	13	2.67
Residues from pulses	229	20	12.80	2.34
Subtotal	26261			368.43
Process residues				
Rice husks	12548	12.4	16.30	179.17
Rice bran	3244	9	13.97	41.24
Sugarcane bagasse	1983	49	18.10	18.31
Coconut shells	11	8	18.53	0.19
Coconut husks	36	11	18.53	0.59
Maize cob	3	15	14	0.04
Maize husks	2	11.1	17.27	0.03
Groundnut husks	16	8.2	15.66	0.23
Subtotal	17843			239.79
Total agricultural crop residues	44104			
Other biomass				
Animal waste	72540	40	13.86	603
Poultry droppings	7300	50	13.50	49.28
MSW	2120	45	18.56	21.64
Total	44186			1282.39

potential is about 1282 PJ. Agricultural residues represent 47% of total biomass energy.

3.4.6. Biomass energy available for electricity generation

It can be concluded that only rice husks, MSW, poultry droppings and bagasse are useful for electricity generation, as field residues are used for fertilizer and animal waste as a cooking fuel in Bangladesh. 50% of the rice husks are used for energy applications such as domestic cooking and steam production for rice parboiling. Therefore, theoretically only 50% of the rice husks can be used for power generation. MSW and bagasse can be used to 100% for grid power generation, as sugar mills are connected to the grid network. A study found that only 57% of poultry droppings are viable for small-scale power generation [67].

3.4.7. Biomass technologies and prospects for power generation

A number of technologies exist for large-scale biomass combustion. Power generation based on biomass combustion employing boiler-steam turbine systems is well established. The current global installed capacity of electricity generation from biomass is about 40 GW [68]. Biomass-based generation technology is well established in the pulp and paper industry as well as in a number of agro-industries, and there is substantial scope for improvement in efficiency. India has launched a sugar-mill-based modern cogeneration program; a capacity of 348 MW has been already commissioned. China has executed some projects for biomass-based electricity generation. By the end of 2002, the total installed capacity of bio-energy power generation there was 2 GW, in which generation from bagasse was 1.7 GW, while the rest was based on crop residues, biogas, landfill gas and MSW [68].

Bangladesh has installed 14 sugar-mill-based cogeneration plants using bagasse. Total power generation capacity is 38.1 MW [69–70]. Bagasse is usually burned to produce steam in sugar-processing operations and to generate electricity to run the sugar mills themselves. The existing mills produce steam in boilers at 15 kg/cm^2 [70]. A study found that an increase in steam pressure in boilers would provide enough steam and electricity to run a typical sugar mill [71]. The excess electricity can be pumped into the national grid. Average crushed-cane capacity per sugar mill is about 1400 tons/day in Bangladesh, and could generate up to 12.75 MW and in total about 178.5 MW.

In the rice processing industry in Bangladesh, there are promising prospects for new biomass technologies. The first rice-husk based off-grid power plant was commissioned in 2007. It is based on a biomass-gasifire internal combustion (IC) engine system and has a rated capacity of 250 kW. It can be estimated that a ton of rice paddy could produce 282 kg dry rice husks with a calorific value of 16.3 MJ/kg. For gasification in gas turbine systems, this residue would generate about 10.6 kW. A survey [72] found that 540 rice mills exist in Bangladesh, and that the capacity ranges from 30 to 120 tons/day. Counting only rice mills with a capacity higher than 30 tons/day, the technical potential of electrical power is about 171 MW.

Methods and technologies for power generation from MSW have developed gradually from traditional ones to advanced ones in the following order: landfill, mass burn incineration, fluidized bed incinerator, gasifire and plasma waste converter. The landfill gas to power technology is the most cost-effective way to deal with a large amount of waste with low calorific value. Landfill technology, as suggested by the ADB mission, seems to be the most preferred technology for Dhaka city [65]. Dhaka city alone has a capacity higher than 5000 tons/day, and the potential power generation is about 20 MW [64–65].

The first biogas plant in Bangladesh was installed in 1972. Since then, several organizations have taken this initiative to research, develop and disseminate biogas technology in the country. Two biogas digester types are commonly used in Bangladesh, e.g., the fixed-dome and floating dome type. Several government-financed biogas projects have been implemented with different degrees of success. Over 25,000 fixed-dome biogas plants have been installed and some large farms produce electricity using this technology. For heating purposes, a medium-size farm is suitable, while larger farms could also produce electricity. Poultry farms that have more than 500 birds could generate about 360 GWh per year which is equivalent to 197 MW considering to run the plants 5 h/day [68].

3.5. Hydro resource potential

The scope of hydropower generation is very limited in Bangladesh. The country is mostly flat, except for some hilly regions in the northeastern and southeastern parts. Furthermore, Bangladesh is a riverine country, and major rivers have a high flow rate for about 5–6 months during the monsoon season, which is substantially reduced during the winter.

3.5.1. Large hydropower potential

This means a capacity higher than 10 MW. At present, 230 MW of hydropower are generated at the Karnafuli hydropower plant, which is the only hydro-electric power plant in Bangladesh; it is operated by the Bangladesh Power Development Board (BPDB). The BPDB is considering extension of this power plant to add another 100 MW capacity. The additional energy will be generated during the rainy season. Two other prospective sites for large hydropower plants at Sangu and Matamuhuri have been identified by the BPDB. It estimates that the potential capacity is 140 MW at Sangu and 75 MW at Matamuhuri.

3.5.2. Small hydropower potential

This means a capacity less than 10 MW. Within this range, hydropower plants are further divided into small hydro- (>3 MW<10 MW), mini hydro- (>300 kW<3 MW), micro hydro- (>5 kW<300 kW), and pico hydro- (<5 kW) power plants that differ with respect to investment cost and annual hydropower availability (Table 8).

3.5.3. Efforts in the development of small hydropower plants

A low-cost 10 kW small hydropower plant was installed by Khoin, a local tribal man, at Monjaipara in the Banderban district. A locally fabricated wooden turbine wheel was employed, and the electricity generated was supplied to 40 households. Currently, Local Government Engineering Department is examining the flow rate in the spillway and exploring the scope for installing a small hydropower plant for the Bamer Chara irrigation project, at Bashkali in the Chittagong district. Recently, BPDB has submitted a

Table 8
Small hydropower potential [35].

Capacity range	Number of sites	Location/region	Total capacity (kW)
Small hydro (3–10 MW)	14	Northeastern region	111000
Mini hydro (300 kW to 3 MW)	11	Mainly at Teesta barrage, Rangpur and northeastern region	12900
Micro hydro	32	Chittagong hill tracts, Sylhet, Dinajpur, Rangpur	798
Pico hydro	1	Lake Fiaz, Chittagong	4
Total			124702

proposal to the government for installation of a 10-kW plant at Barkal, Rangamati and a 25-kW plant at the Teesta barrage, Rangpur.

4. Technologies not covered

A few technologies, e.g., fuel cells, solar thermal, geothermal and tidal, have not been covered in this study mainly due to the following reasons:

1) Technical know-how has not yet matured and spread all over the world-wide. Full-scale commercial activities will take some time to pick them up. At the initial stages such technologies are expensive. This is important for countries like Bangladesh, where there is a financial crunch restricting the freedom of experimenting with new technologies.
2) In the case of technologies like solar thermal power, better uses like water heating, crop drying etc., exist that are more accepted and better proven than power generation. However, a few solar thermal power plants are operation in some countries, but most of them are more in the form of pilot projects than commercial ventures.
3) Know-how on other technologies like geothermal, tidal and wave energy exists and Bangladesh needs to investigate their potentiality. However, a limited supply of technologies and other technical barriers hinder their application in Bangladesh.

5. Concluding remarks

The future economic development trajectory for Bangladesh is likely to result in a rapid and accelerated growing energy demand, with attendant shortages and problems. Due to the predominance of fossil resources in the energy mix, there are negative environmental externalities caused by electricity generation. At the same time, the country has very limited fossil fuel reserves to generate electricity. In this context, it is imperative to develop and promote alternative energy resources that can lead to sustainable and environmentally friendly energy systems. There are opportunities for renewable energy technologies for power generation under the climate change regime as they meet two basic conditions to be eligible for assistance under the Clean Development Mechanism (CDM) of UNFCCC: they contribute to the mitigation of global climate change through the reduction of GHG emissions, and they confirm to national priorities by leading to the development of local capacities and infrastructure.

It is clear from this study that a large potential exit for grid-connected solar PV in Bangladesh. However, a technology with a high probability of adoption will not automatically be implemented as a result of the fact that the technology diffusion process is not only depending on the attributes of the technology itself, but also is influenced by various social, economic, institutional and political factors.

The renewable energy resources may serve to supplement the long-term energy needs of Bangladesh to a significant level. An integrated energy planning approach, consistency in government energy policies and rational policy instruments to deal with techno-economic and socio-political barriers are the pre-requisites for long-term sustainable development of the renewable energy technologies for power generation.

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