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**Article**

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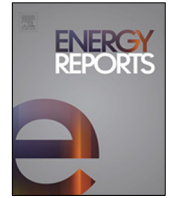
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## Research paper

# Energy, exergy and sustainability analyses of Bangladesh's power generation sector



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## ABSTRACT

Ensuring sustainability in electrical power generation is a major concern in the modern world. Reducing energy depletion from power generation can reduce emissions and contribute to sustainability. Exergy analysis can be used to assess and optimize energy systems and thus can help achieve sustainability. In this analysis, energy and exergy utilization of Bangladesh's utility sector is investigated based on data from 2007 to 2016. The overall energy efficiencies vary from 34.9% to 36.3% while the exergy efficiencies vary from 35.0% to 39.2% within this period. Thermal power plants are seen to have greater exergetic improvement potential than hydro power plants. To correlate between exergy and environmental sustainability, this study applies several exergetic parameters as sustainability indicators. It is found that the depletion number varies between 0.61 and 0.65 while the exergy sustainability index varies between 1.54 and 1.64. The relative irreversibility and lack of productivity are greater for gas operated power plants than other thermal power plants. The largest relative irreversibility is 0.90 while the largest lack of productivity is 1.72. The waste exergy ratio varies from 0.48 to 0.59 while the environmental effect factor varies from 1.35 to 1.68. Renewable power generation is found to have a higher sustainability than fossil fuel power generation. It is believed that current analysis can serve as a benchmark to help attain power generation sustainability.

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## 1. Introduction

Energy efficiency is of increasing interest around the world. Efficient use of energy not only reduces waste but also saves money. Nowadays, many countries are trying to shift from the excessive use of fossil fuels as they cause many environmental problems including global warming (Hossain et al., 2019). Many countries are also trying to enhance the energy efficiency of their processes and sectors. Identifying energy losses in processes and taking appropriate measures to bring about policy change can help a society become more sustainable in the future. Reducing energy loss can also help in reducing environmental pollution and its consequences. Sectors and processes that are responsible for energy waste need to be identified in order to reduce these losses.

Exergy analysis is a convenient technique for determining losses within a sector. Exergy can be defined as the maximum useful energy that can be obtained from a system as it comes to equilibrium with its surroundings (Ahamed et al., 2011; Rosen, 2011, 2012). Energy analysis is incapable of determining the true losses associated with a process. Exergy analysis can identify the magnitude of thermodynamic losses and processes that are responsible for them. Identifying exergy loss can help in identifying future improvements (Kanoğlu et al., 2005; Dincer and Rosen, 2013).

Globally, many processes and sectors have been analyzed via exergy methods. For example, exergy analysis and extended exergy analysis (EEA) have been applied in assessing the exergetic efficiency of a wind power plant in northern Iran (Aghbashlo et al., 2017). The study found that the irreversibility based on standard exergy analysis is smaller than the EEA based irreversibility. An exergy-based optimization of an innovative oxy

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## Nomenclature

CEC	Cumulative exergy consumption (PJ)
CEL	Cumulative exergy loss (PJ)
EEF	Environmental effect factor
$E^W$	Exergy flow associated with work (kJ)
$E^Q$	Exergy flow for heat energy (kJ)
H	Higher heating value (kJ/kg)
LOP	Lack of productivity
m	Mass of fuel (kg)
NRES	Non-renewable exergetic share
$P_0$	Atmospheric pressure (Pa)
$Q_r$	Heat transfer (kJ)
RES	Renewable exergetic share
RI	Relative irreversibility
ESI	Exergy sustainability index
$T_0$	Ambient temperature (K)
W	Work (including shaft work, electricity) (kJ)
WER	Waste exergy ratio

## Greek symbols

$\eta$	Energy efficiency
$\varphi$	Exergy efficiency
$\gamma$	Exergy grade function
$\varepsilon$	Specific exergy (kJ/kg)

## Subscripts

e	Electrical
h	Hydro
o	Overall
t	Thermal

## Acronyms

BPDB	Bangladesh Power Development Board
EEA	Exergy and extended exergy
HSD	High speed diesel
SKO	Superior kerosene oil

combustion power plant was investigated by Presciutti et al. (2018). Exergy, exergoeconomic and exergoenvironmental analyses were employed for a hydrogen liquefaction process and it was suggested to modify the turbo expanders and compressors to increase the productiveness of the process (Ansarinabas et al., 2018). Exergy based solar energy potential was calculated for India by Jamil and Bellos (2018). Exergy based resource and environmental management for a hospitality industry and other factories was examined by Stylos et al. (2018) and Khattak et al. (2016). The impact of changing reference environment temperature on the exergy efficiency of a horizontal ground heat exchanger was studied by Esen et al. (2007).

Sectoral exergy analysis was first introduced by Reistad (1975) to investigate energy and exergy efficiencies for US sectors (Rosen, 1992). Nowadays, exergy analysis is performed throughout the globe to calculate the energy and exergy effectivenesses of nations and their economic sectors. Table 1 lists some of the studies regarding sectoral exergy analysis.

From Table 1 it is observed that several studies have been conducted on the utility sector of numerous countries. Exergy based sustainability analyses of this sector were not done in the previous analyses. The affinity between exergy and sustainability

is increasingly recognized, as enhancing the exergy effectiveness of a system helps improve its sustainability.

The objective of this article is to address the above shortcoming by applying exergy analysis to the utility sector of Bangladesh. No other studies have been reported that discuss Bangladesh's utility sector. In this study, exergy losses from various fuels to the surroundings are shown using energy and exergy flow diagrams. Various exergetic sustainability parameters are utilized to assess the sustainability of this sector. The implementation of sustainability indicators in conventional sectoral exergy analyses is novel. These indicators can help researchers gain insights on impending developments of a sector and assess the effect of waste energy on the environment. The impact of renewable and non-renewable energy sources in power generation can be determined using the indicators from this study. The authors expect that the current study will serve as a benchmark for the assessment of sustainability of this sector. Energy planners and researchers of Bangladesh and other countries will likely be able to use the results to investigate the true energy utilization efficiency of the utility sector and introduce appropriate policies for energy conservation and management.

## 2. Overview of Bangladesh's utility sector

Bangladesh is known for its substantial stores of natural gas. About 63% of the nation's electricity is generated from natural gas. Fig. 1 presents the percentage of electricity generated by various fuels in Bangladesh. As of 2017, the country's total installed capacity was 13,151 MW (Anon, 2019b, <http://sari-energy.org>). The residential sector is the foremost user of grid electricity, at about 51.0%, followed by industrial sector at 34.3%. Table 2 breaks down energy consumption by sector (Anon, 2019a, [www.sreda.gov.bd](http://www.sreda.gov.bd)). Most existing power plants are gas fired and some are oil fired. Due to heavy usage of gas in the residential, utility, and transportation sectors, the existing reserves of gas are decreasing. The government is also trying to minimize the consumption of natural gas and seeking alternative ways to produce electricity. Currently, the government is focusing on promoting renewable electricity production (Islam and Khan, 2017). Bangladesh has only one hydro power plant, of 230 MW capacity, in Kaptai. Currently, a nuclear power plant of 2000 MW is under construction in Rooppur in collaboration with Russia.

## 3. Energy and exergy analyses

### 3.1. Basic parameters of exergy analysis

In the following subsection, some fundamental parameters for exergy analysis are discussed. The parameters are derived from Rosen (1992) and Dincer et al. (2004b).

#### 3.1.1. Exergy of heat

At a constant temperature  $T_p$ , the thermal exergy transferred with heat transfer  $Q_p$  can be written as:

$$E^Q = (1 - T_0/T_p)Q_p \quad (1)$$

#### 3.1.2. Exergy of work

The exergy of work (W) is the same as its energy. That is,

$$E^W = W \quad (2)$$

#### 3.1.3. Chemical exergy

At the reference environment temperature and pressure, the specific physical exergy of a material is zero. At this condition, the specific exergy  $\varepsilon_{ff}$  of hydrocarbon fuels reduces to the chemical exergy, and can be written as

$$\varepsilon_{ff} = \gamma_{ff}H_{ff} \quad (3)$$

Typical values of  $\gamma_{ff}$  for selected fuels are presented in Table 3.

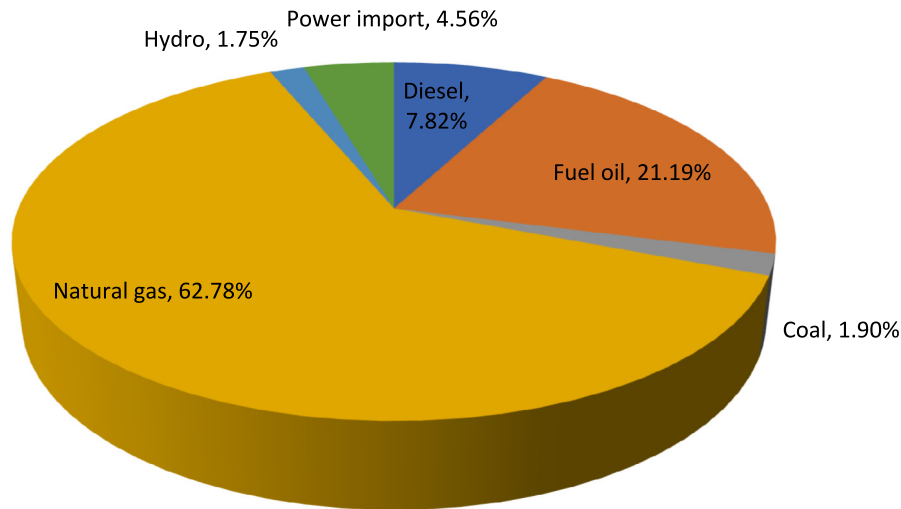


Fig. 1. Electricity generation from various types of fuels in Bangladesh in 2016.

Table 1

Past studies involving sectoral exergy analysis.

Authors	Country	Sectors
Nielsen and Jørgensen (2015)	Denmark (Island of Samsø)	Energy, agriculture, public, private, trade, nature
Mosquim et al. (2018)	Brazil (Sao Paulo state)	Industrial, rural, commercial and public, residential and transportation
Miranda et al. (2018)	Mexico	Industrial
Bühler et al. (2016)	Denmark	Industrial
Motasemi et al. (2014)	Canada	Transport
Byers et al. (2015)	United Kingdom	Transport
Liu et al. (2014)	China	Urban residential
Amoo and Fagbenle (2014)	Nigeria	Transport
Causone et al. (2017)	Italy (Milano smart city)	Residential, commercial, service and public, transport
Liu et al. (2017)	China	Agriculture
Gong and Wall (2016)	Sweden	Transport, residential, agricultural, industrial
Zhang et al. (2019)	China	Agriculture
Flórez-Orrigo et al. (2015)	Brazil	Transport
Utlu and Hepbasli (2007)	Turkey	Utility
Saidur et al. (2007)	Malaysia	Commercial and utility
Dincer et al. (2004a)	Saudi Arabia	Utility
Al-Ghandoor et al. (2009)	Jordan	Utility
Avara and Karami (2010)	Iran	Utility

Table 2

Grid electricity consumption breakdown by sector ([www.sreda.gov.bd](http://www.sreda.gov.bd)).

Sector	Electricity consumption (%)
Industry	34.3
Transport	0.0
Residential	51.0
Commercial	9.9
Agriculture	4.8

Table 3

Typical values of  $\gamma_{ff}$  for fuels encountered in the present study (Rosen and Dincer, 1997; Utlu and Hepbasli, 2005).

Fuel	Exergy factor
Coal	1.06
Natural gas	0.93
Kerosene	0.99
Diesel	1.07
Fuel oil	0.99
Hydro	1

### 3.1.4. Reference environment

A reference environment must be specified for the evaluation of exergy, and this is often based on the natural environment for the location under consideration. Taking into account Bangladesh's climatic conditions, minor modifications are made to the model developed by Gaggioli and Petit (1977), which is

recommended by Rosen (1992) and Dincer et al. (2004c). In the current study, the temperature and pressure of the reference environment, which is taken to be the natural surroundings, are considered as  $T_0=25^\circ\text{C}$  and  $P_0 = 100 \text{ kPa}$ , respectively. The chemical composition is taken to be air saturated with water

vapor, as well as the following condensed phases at 25°C and 100 kPa: water (H<sub>2</sub>O), gypsum (CaSO<sub>4</sub>·2H<sub>2</sub>O) and limestone (CaCO<sub>3</sub>).

### 3.1.5. Energy and exergy efficiencies

For most processes, the energy efficiency can be taken to be the ratio of energy in products to the total energy input while the exergy efficiency can be taken to be the ratio of exergy in products and the total exergy input. These efficiencies as written by Eqs. (4) and (5) respectively (Rosen, 1992; Dincer et al., 2004b):

$$\text{Energy efficiency, } \eta = \frac{\text{Energy in products}}{\text{Total energy input}} \quad (4)$$

$$\text{Exergy efficiency, } \varphi = \frac{\text{Exergy in products}}{\text{Total exergy input}} \quad (5)$$

### 3.2. Improvement potential

According to Van Gool (1997), reducing irreversibilities helps raise the exergy efficiency of a process. The exergetic improvement potential, IP, was presented by Van Gool for investigating a system. It is written as:

$$IP = (1 - \varphi)(\text{Exergy input} - \text{Exergy output}) \quad (6)$$

The improvement potential is also presented by Van Gool, and can be written as

$$IP = (1 - \varphi)^2 \times \text{Exergy Input} \quad (7)$$

### 3.3. Sustainability indicators

Exergy analysis is an assessment method which identifies the irreversibilities of a sector. Reducing these losses can lead to more efficient utilization of energy resources. Development is more sustainable when resources are utilized effectively (Rosen et al., 2008).

Sustainability can be achieved by reducing exergy losses associated with fossil fuel utilization (Cornelissen, 1997). Connelly and Koshland (1997) first applied the depletion number to deduce the effectiveness of fossil fuel utilization. "The depletion number is defined as the ratio of exergy destroyed to the exergy input" (Rosen et al., 2008). This indicator is used to measure the effectiveness of fossil fuel utilization and has an inverse relationship with exergy efficiency. That is, the higher the exergy efficiency of a system, the lower is the exergy destruction and depletion number. The depletion number can be written as

$$\text{Depletion number, } D = \frac{\text{Exergy Destroyed}}{\text{Exergy Input}} \quad (8)$$

or

$$D = (1 - \varphi) \quad (9)$$

The exergy sustainability index is inversely proportional to the depletion number. ESI can be used to measure the quality of the process considering mass and energy conservation principle. ESI is closely interconnected with sustainable development. Higher value of ESI represents lower depletion of resources and lower environmental impact. Hence, we can write

$$\text{Exergy sustainability index, ESI} = \frac{1}{\text{Depletion number}} \quad (10)$$

Xiang et al. (2004) state that lack of productivity and relative irreversibility are indicators that can show the impact of useful and destroyed exergy on sustainability, where:

$$\text{Relative irreversibility, RI} = \frac{\text{Exergy}_{\text{destroyed}}^{\text{Individual}}}{\sum \text{Exergy}_{\text{destroyed}}} \quad (11)$$

$$\text{Lack of productivity, LOP} = \frac{\text{Exergy}_{\text{destroyed}}^{\text{Individual}}}{\sum \text{Exergy}_{\text{product}}} \quad (12)$$

The waste exergy ratio and environmental effect factor are other sustainability indicators that are applied by researchers to investigate the impact of waste exergy on the environment (Aydin et al., 2015; Midilli and Kucuk, 2015). The former parameter can be determined as follows:

$$\text{Waste exergy ratio} = \frac{\text{Total exergy out}}{\text{Total exergy inlet}} \quad (13)$$

Here, the total exergy out is calculated as:

$$\text{Total exergy out} = \text{Total inlet exergy} - \text{Total output exergy} \quad (14)$$

The environmental effect factor is determined as:

$$\text{Environmental effect factor} = \frac{\text{Waste exergy ratio}}{\text{Exergy efficiency}} \quad (15)$$

The renewable exergy share (RES) and non-renewable exergy share (NRES) are parameters that address the effects of renewable and non-renewable fuel consumption on the sustainability of the environment. The parameters can be written as (Zisopoulos et al., 2017):

$$\text{RES} = \frac{\text{Renewable exergy consumption}}{\text{Total exergy consumption}} \quad (16)$$

$$\text{NRES} = \frac{\text{Non-renewable exergy consumption}}{\text{Total exergy input}} \quad (17)$$

Cumulative exergy loss (CEL) indicates the amount of available energy that is lost in a process or sector. A higher CEL signifies lower sustainability. CEL can be written as follows (Zisopoulos et al., 2017):

$$\text{CEL} = \text{Cumulative exergy consumption (CEC)} - \sum \text{Useful Exergy} \quad (18)$$

Here, CEC is expressed as:

$$\text{CEC} = \sum \text{Exergy}_{\text{input}} \quad (19)$$

## 4. Methodology and data sources

### 4.1. Data sources

Required data for this study are taken from the annual reports of the Bangladesh Power Development Board (BPDB). This institution publishes an annual report of energy consumption and generation in the utility sector every year. In this analysis, annual reports from 2006–2016 are used. However, energy input data of the lone hydropower plant in Bangladesh are calculated from monthly operational data of the plant. The efficiency of the hydro power plant is presumed to be constant. In this analysis, we assume the efficiency to be 85%, which is a typical value (Avara and Karami, 2010). Energy consumption and electricity production data of various fuel based power plants are shown in Table 4. Solar and wind energy generation are negligible in comparison with thermal and hydropower plants for these periods. So those energy resources are not taken into account in this study.

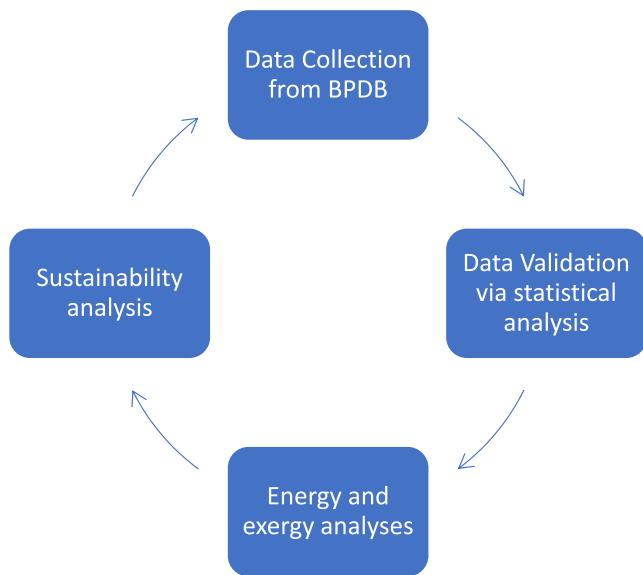
Table 5 shows exergy input and output of the various fuels used in the utility sector. The exergy consumption and output are calculated by multiplying the energy output and input data from Table 4 by the quality factor from Table 3.

**Table 4**  
Energy use (input) and electricity generation (output) data for the utility sector in Bangladesh from 2007 to 2016 ([www.bpdb.gov.bd](http://www.bpdb.gov.bd)). Energy data are in Petajoules.

Year	Gas		Fuel oil		High speed diesel		Coal		Superior kerosene oil		Hydro	
	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input
2007–08	78.4	227.74	4.61	11.75	0.99	4.25	4.22	13.08	0.05	0.22	3.43	4.04
2008–09	84.4	246.20	3.69	10.98	1.89	6.33	4.22	13.08			1.5	1.76
2009–10	90.53	268.76	3.14	8.25	1.87	6.70	4.26	14.04			2.64	3.10
2010–11	88.31	260.1	6.55	18.67	7.84	23.79	3.26	12.16			3.15	3.71
2011–12	97.48	285.1	16.12	35.3	5.40	16.03	3.68	13.74			2.81	3.31
2012–13	104.7	301.57	18.54	45.92	3.73	10.52	4.75	17.25			3.23	3.80
2013–14	103.43	301.97	22.11	57.	5.52	16.71	3.74	13.56			2.12	2.49
2014–15	106.28	313.9	26.26	66.34	7.32	25.19	0.19	0.76			2.04	2.40
2015–16	120.62	354.12	31.22	76.69	8.59	30.03	3.05	12.5			3.46	4.08

**Table 5**  
Exergy input and exergy output in the utility sector from 2007 to 2016. Units are in Petajoules.

Year	Gas		Fuel Oil		HSD		Coal		SKO		Hydro	
	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input
2007–2008	72.87	211.8	4.56	11.63	1.06	4.54	4.47	13.87	0.05	0.22	3.43	4.04
2008–2009	90.73	229	3.66	10.87	2.02	6.78	4.47	13.86			1.50	1.76
2009–2010	84.19	249.94	3.14	8.16	2.0	7.17	4.52	14.88			2.64	3.10
2010–2011	82.13	241.88	6.48	18.49	8.39	25.45	3.46	12.89			3.15	3.71
2011–2012	90.66	265.19	15.96	34.93	5.78	17.16	3.90	14.56			2.81	3.31
2012–2013	97.37	280.46	18.35	45.46	4.0	11.26	5.04	18.29			3.23	3.80
2013–2014	96.19	280.82	21.89	56.4	5.91	17.88	3.96	14.38			2.12	2.49
2014–2015	98.84	291.94	26.0	65.67	7.83	26.96	0.21	0.81			2.04	2.40
2015–2016	112.18	329.34	30.91	75.92	9.19	32.13	3.23	13.24			3.46	4.08



**Fig. 2.** Overall methodology of the study.

#### 4.2. Methodology

Data obtained from BPDB were validated by statistical analysis. Then energy, exergy and sustainability analyses were applied for this sector. To perform energy analysis, the procedures used by Dincer et al. (2004a) and Saidur et al. (2007) are utilized. Equations (4) and (5) are used for determining energy and exergy efficiencies for each year. The energy efficiencies of the hydro and thermal power plants along with overall efficiencies are determined using data from Table 4. Similarly, exergy efficiencies of thermal and hydro power plants and overall exergy efficiencies are determined using data from Table 5, based on the methodology employed in Utlu and Hepbasli (2007). Exergetic parameters are applied to investigate sustainability of this sector. The overall methodology of this study is described in Fig. 2.

## 5. Results and discussion

### 5.1. Energy and exergy efficiencies

In this section, energy and exergy efficiencies for Bangladesh's utility sector are determined via Eqs. (4) and (5), and data from Table 4. A sample calculation for the year 2012–2013 is given below:

For thermal power plants:

$$\begin{aligned}\eta_{e,t} &= \text{Electrical energy generated/Total input energy} \\ &= 131.72/375.26 \\ &= 35.1\%\end{aligned}$$

For hydropower plants,

$$\begin{aligned}\eta_{e,h} &= \text{Electrical energy generated/Total energy input in} \\ &\quad \text{hydro power plant} \\ &= 3.23/3.80 \\ &= 85.0\%\end{aligned}$$

The overall energy efficiency is:

$$\begin{aligned}U_{\eta o} &= \Sigma(\text{Fraction of electricity generated in each subsector} \\ &\quad \times \text{Each subsector efficiency}) \\ &= 0.98 \times 35.1 + 0.02 \times 85.0 \\ &= 36.1\%\end{aligned}$$

For calculating the overall exergy efficiency, data from Table 5 are utilized. A sample calculation for 2012–2013 is shown below:

For thermal power plants:

$$\begin{aligned}\varphi_{e,t} &= 124.78/355.47 \\ &= 35.1\%\end{aligned}$$

For hydropower plants:

$$\begin{aligned}\varphi_{e,h} &= 3.23/3.80 \\ &= 85.0\%\end{aligned}$$

The overall exergy efficiency is:

$$\begin{aligned}U_{\varphi o} &= \Sigma(\text{Fraction of electrical exergy generated in each} \\ &\quad \text{subsector} \times \text{Each subsector efficiency}) \\ &= 0.97 \times 35.1 + 0.03 \times 85.0 \\ &= 36.6\%\end{aligned}$$

With the above procedure, energy and exergy efficiencies for other years are determined. The overall energy and exergy efficiencies of Bangladesh's utility sector from 2007–2016 are shown in Fig. 3. From Fig. 3 it is evident that energy efficiencies vary between 34.9% and 36.3% while exergy efficiencies vary between

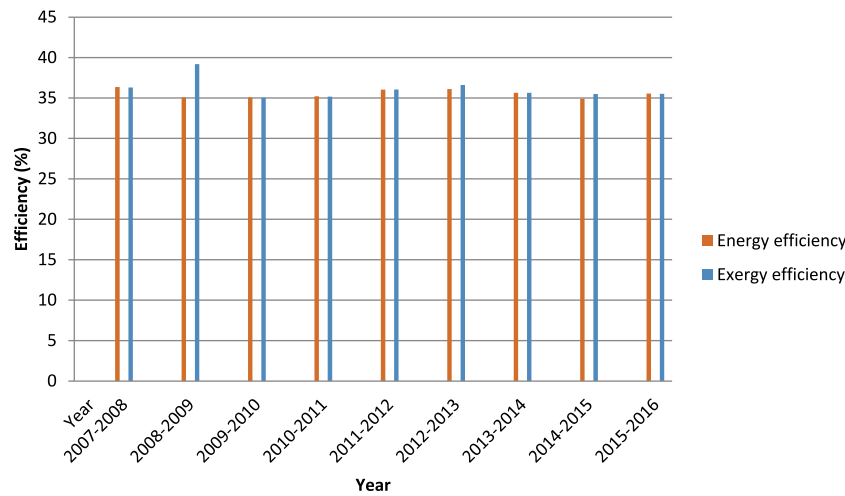


Fig. 3. Overall energy and exergy efficiencies of Bangladesh's utility sector from 2007–2016.

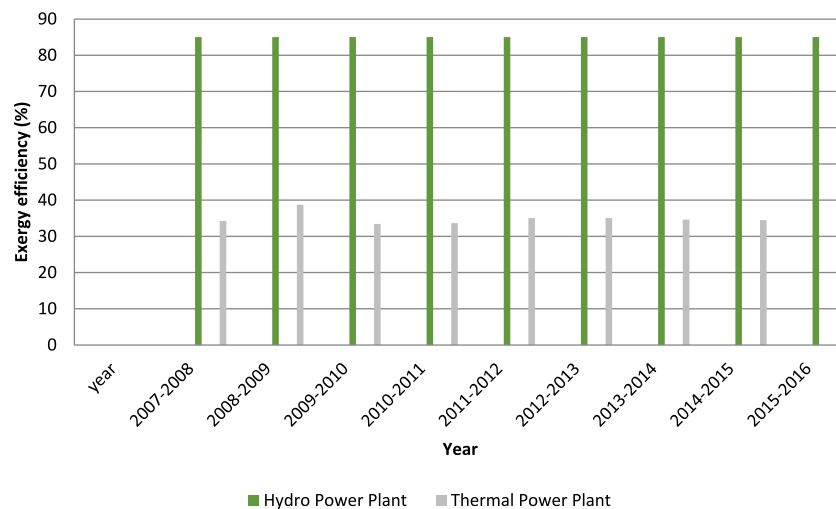


Fig. 4. Exergy efficiencies of thermal and hydro power plants for Bangladesh from 2007 to 2016.

35.0% and 39.1% within this period. The highest exergy efficiency was observed in 2008–2009. The efficiencies those years were higher as more hydro energy was converted to products and losses were lower. Several exergy efficiencies are higher than the energy efficiencies as the amount of exergy use is greater than the energy use.

From Fig. 4 it is evident that the hydropower plant is more energy and exergy efficient than thermal power plants, for the same reference environment conditions. This is mainly due to the high irreversibilities associated with thermal power plants. Saidur et al. (2007) notes that the hydro power plant is more efficient on an exergy basis due to the appropriate matching of kinetic energy in the application with the quality of the energy resources employed. For efficiency calculations, some reference conditions must be considered. These conditions may vary from the design and operational points of view. Furthermore, operational strategies and management can give a clear picture of the efficient operation of systems and processes (Utlu and Hepbasli, 2007).

Several investigators have obtained results similar to those presented here, showing that the energy and exergy efficiencies are almost identical for the utility sector. The key importance of this result is that inefficiencies are caused not by the mismatch in the input and output quality levels, but instead by the techniques presently available for the conversion processes

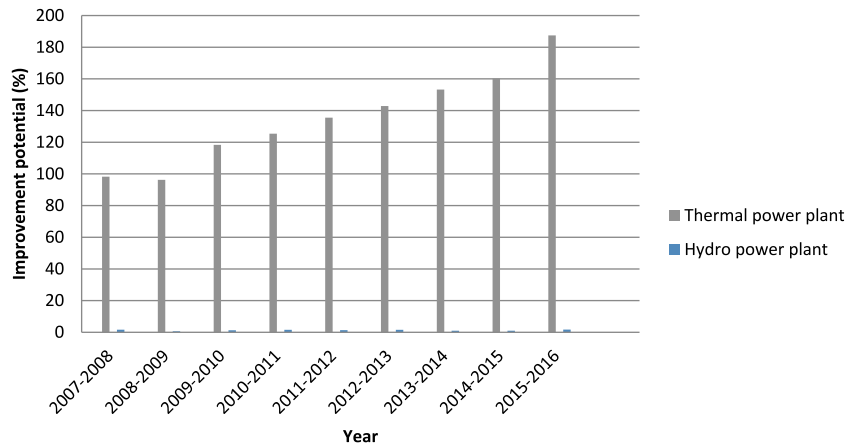
(Utlu and Hepbasli, 2007). Development in this sector is predicted to be challenging and will include significant modifications in generation methods. Bangladesh's utility sector mainly depends on fossil fuels and hydro to fulfill its energy demand. The share of other renewable energy resources like wind and biomass are lower compared to that of hydro resources.

## 5.2. Comparison with other countries

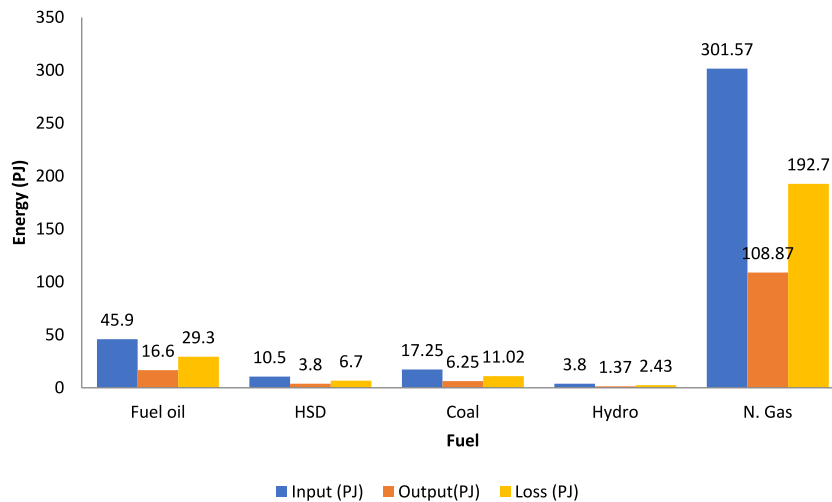
The utility sector of Bangladesh is compared with other countries based on energy and exergy efficiencies. In Table 6 it is seen that Bangladesh's utility sector is less exergy efficient than those of Norway, Canada, Turkey and Japan. These countries have major contributions of electricity from hydropower plants. Canada and Japan have nuclear power plants. Norway has a higher utility sector exergy efficiency of 76% as it has no thermal power plants (Saidur et al., 2007; Ertesvag, 2001). Note that Saudi Arabia has a less exergy efficient utility sector than Bangladesh. This is mainly because Saudi Arabia's electricity generation is mainly fossil fuel driven and the amount of exergy loss is higher in thermal power plants. Bangladesh's utility sector is also fuel dependent but the share of hydroelectricity is greater than that in Saudi Arabia. Energy production and consumption are also lower for Bangladesh than Saudi Arabia.

**Table 6**  
Energy and exergy efficiencies of the utility sector of selected countries.

Country	Average energy efficiency (%)	Average exergy efficiency (%)	Years analyzed	References
Iran	33–39	33.4–39.3	1994–2006	Avara and Karami (2010)
Turkey	45	45	1995	İlerî and Gürer (1998)
Malaysia	32–42	32.4–42	1990–2003	Saidur et al. (2007)
Norway	76.6	76	2000	Ertesvag and Mielnik (2000)
Saudi Arabia	31.8	31.7	2000	Dincer et al. (2004b)
Canada	–	53	1986	Rosen (1992)
Jordan	32–36	32–36	1989–2006	Al-Ghandoor et al. (2009)



**Fig. 5.** Improvement potential of hydro and thermal power plants from 2007–2008 to 2015–2016.



**Fig. 6.** Energy flows for the Bangladesh utility sector for the year 2012–2013.

### 5.3. Improvement potential of utility sector

The improvement potentials of Bangladesh's utility sector have been calculated over the period 2007–2016, using Eq. (7) and exergy input data from Table 5. The improvement potentials are shown in Fig. 5. It is seen that the improvement potential is greater for thermal power plants than hydro power plants. The improvement potential of thermal power plants increases with time. The improvement potential was 99.0% in 2007–2008 and reached maximum value of 187.5% in 2015–2016. This suggests that a great amount of energy can be saved from thermal power plants by proper fuel selection and by introducing advantageous energy generation techniques such as using combined cycles, switching to natural gas and utilization of modern components. The increasing improvement potential also indicates

that exergy losses are increasing with time. As the power plants age, the power generation capabilities are decreasing. In the hydropower plant, the irreversibilities are lower than in thermal power plants. The improvement potential was 1.64% in 2007–2008 and increased to a value of 1.70% in 2015–2016.

### 5.4. Energy and exergy losses in the utility sector

Exergy is destroyed in irreversible processes and conserved in reversible processes. Figs. 6 and 7 show respectively the energy loss and exergy loss in the utility sector for the year 2012–2013. From Fig. 6 it is seen that energy loss in natural gas operated power plants is high, reaching 192.7 petajoules. About 36% of energy was converted to product and 64% was lost to the surroundings. As power plants age, energy loss rises. These plants



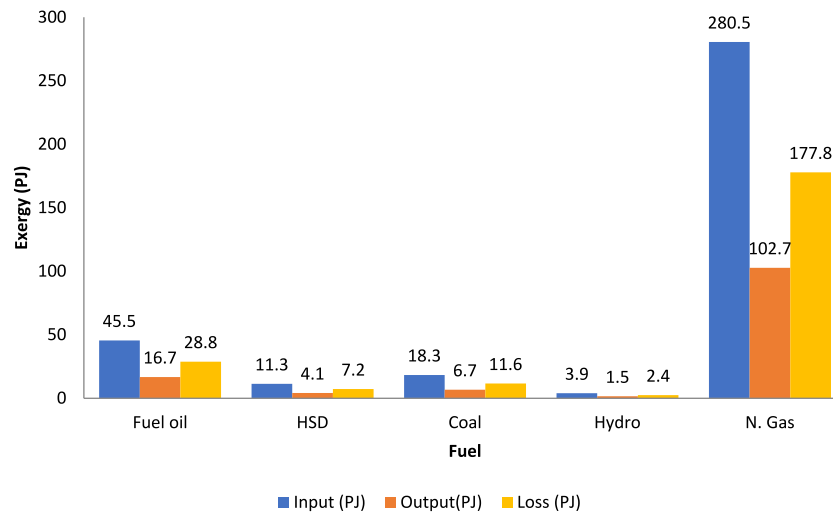


Fig. 7. Exergy flows for the Bangladesh utility sector for the year 2012–2013.

use old equipment to generate electricity, so large amounts of energy are lost.

From Fig. 7 it is evident that exergy loss in natural gas power plants is also high. About 177.8 petajoules of exergy were destroyed and 102.6 petajoules were converted into product. The main reason losses are high is that the gas operated power plants are extensively used. This is also compounded by the fact that equipment used for energy generation in many utility plants is not modern. Higher rate of exergy losses signifies that higher thermodynamic imperfections and higher entropy generation associated with the power generation process. With increase in exergy loss and entropy generation, the net heat duty will increase. This is due to higher irreversibilities associated with the combustion process. The exergy loss from the hydro power plant is also noteworthy as it is a renewable form of energy. This hydro power plant operates with old equipment to generate electricity. The transmission and other losses are also higher in this power plant. Using modern machinery for power generation can reduce the exergy loss of this power plant.

### 5.5. Sustainability analysis

This section details the sustainability analysis of Bangladesh's utility sector. Depletion number, ESI, RI, LOP, WER, EEF, RES, NRES and CEL are utilized as sustainability parameters. Table 7 shows the depletion number and ESI for Bangladesh's utility sector. It is observed that depletion number varies between 0.61 and 0.65 whereas ESI varies from 1.54 to 1.64. The depletion number suggests that about 60.8% to 65.0% of fossil fuels are depleted in this sector. The large amounts of exergy loss from inefficient and old equipment are the main reason for the higher depletion number. A higher depletion number suggests decreasing it can have a positive impact on exergetic sustainability (Mascarenhas et al., 2019; Chowdhury et al., 2019a,b). The ESI is low as the depletion numbers are high due to the higher exergy loss. If exergy losses are reduced and the fossil fuel utilization rate is increased, the exergy efficiency of the process and ESI increase. To ensure maximum sustainability of this sector, the depletion number should be lowered, and brought closer to zero (Chowdhury et al., 2020).

Tables 8 and 9 show RI and LOP respectively for several power plants of Bangladesh's utility sector. From Table 8 it is observed that RI is higher in gas operated power plants. A large quantity of exergy loss from these power plants is due to improper design and usage of old equipment which are responsible for the higher

Table 7  
Depletion number and ESI for Bangladesh's utility sector.

Year	Depletion number	ESI
2007–2008	0.64	1.57
2008–2009	0.61	1.64
2009–2010	0.65	1.54
2010–2011	0.65	1.54
2011–2012	0.64	1.56
2012–2013	0.63	1.58
2013–2014	0.64	1.55
2014–2015	0.65	1.55
2015–2016	0.65	1.55

RI. The highest RI of 0.89 occurred in 2009–2010. It can be seen that RI varies from 0.89 to 0.73. This is because many new plants have been installed with modern machinery and modern methods are applied for energy generation, resulting in decreased exergy losses. The RI for the hydro power plant is lower as exergy losses from this plant are lower. Reducing irreversibility in energy generation process, especially for combustion, may reduce the exergy loss and the RI (Chowdhury et al., 2019c,d).

Table 9 shows the lack of productivity (LOP) of Bangladesh's utility sector. From Table 8 it is observed that the LOP of the gas power plant ranges between 1.35 and 1.72. The LOP suggests an inability of the system to convert the input to useful product. As exergy destructions are higher in the gas power plants than in other power plants, the LOP is higher. From Table 9 it is observed that the LOP in fuel oil power plants is increasing with time and achieved a peak value of 0.29 in 2015. The hydro power plant exhibits a low LOP as exergy losses are lower in this plant.

Table 10 shows the waste exergy ratio (WER) and environmental effect factor (EEF) of the power plants. From Table 10 it is observed that WER and EEF are maximum for gas operated power plants. WER varies between 0.48 and 0.59 while EEF varies between 1.35 and 1.68. WER is higher as it is a function of exergy loss, and EEF is higher since WER is higher. As the largest amount of exergy is lost from gas operated power plants, WER is high. EEF indicates the impact of waste exergy on the environment. The hydro power plant has lower WER (0.003–0.0001) and EEF (0.003–0.006) values, as the exergy loss from this power plant is lower. Table 11 shows RES, NRES and CEL values of the utility sector of Bangladesh. RES is significantly lower as the greatest amount of exergy is obtained from fossil fuels (i.e., about 98%). The higher value of NRES gives rise to higher values of CEL and depletion number. RES was lower (0.62%) in 2014–2015 and so

**Table 8**  
RI for Bangladesh's utility sector.

Year	Gas	Fuel oil	HSD	Coal	SKO	Hydro
2007–2008	0.87	0.04	0.02	0.06	0001	0.003
2008–2009	0.86	0.05	0.03	0.06		0.002
2009–2010	0.89	0.03	0.03	0.05		0.003
2010–2011	0.80	0.06	0.09	0.05		0.003
2011–2012	0.81	0.09	0.05	0.04		0.001
2012–2013	0.79	0.12	0.03	0.05		0.01
2013–2014	0.76	0.14	0.05	0.04		0.01
2014–2015	0.76	0.16	0.07	0.002		0.001
2015–2016	0.73	0.15	0.08	0.03		0.01

**Table 9**  
LOP of power plants of Bangladesh's utility sector.

Year	Gas	Fuel oil	HSD	Coal	SKO	Hydro
2007–2008	1.61	0.08	0.04	0.11	0.002	0.007
2008–2009	1.35	0.07	0.05	0.09		0.003
2009–2010	1.72	0.05	0.05	0.11		0.005
2010–2011	1.54	0.12	0.16	0.09		0.005
2011–2012	1.47	0.16	0.10	0.09		0.004
2012–2013	1.43	0.21	0.06	0.10		0.004
2013–2014	1.42	0.27	0.09	0.08		0.003
2014–2015	1.43	0.29	0.14	0.004		0.003
2015–2016	1.37	0.22	0.08	0.07		0.002

**Table 10**  
Waste exergy ratio (WER) and environmental effect factor (EEF) of the thermal and hydro power plants in Bangladesh.

Year	Gas		Fuel oil		HSD		Coal		SKO		Hydro	
	WER	EEF	WER	EEF	WER	EEF	WER	EEF	WER	EEF	WER	EEF
2007–2008	0.53	1.46	0.03	0.08	0.01	0.03	0.04	0.11	0.0007	0.002	0.003	0.008
2008–2009	0.53	1.35	0.03	0.08	0.02	0.05	0.04	0.10			0.001	0.003
2009–2010	0.59	1.68	0.02	0.06	0.02	0.06	0.04	0.11			0.002	0.006
2010–2011	0.53	1.51	0.04	0.11	0.06	0.17	0.03	0.09			0.002	0.006
2011–2012	0.52	1.44	0.06	0.17	0.03	0.08	0.03	0.08			0.001	0.003
2012–2013	0.51	1.39	0.08	0.22	0.02	0.05	0.04	0.11			0.002	0.005
2013–2014	0.50	1.40	0.09	0.25	0.03	0.08	0.03	0.08			0.0001	0.003
2014–2015	0.50	1.41	0.10	0.25	0.05	0.08	0.002	0.08			0.0009	0.003
2015–2016	0.48	1.35	0.10	0.28	0.05	0.14	0.02	0.006			0.001	0.003

**Table 11**  
RES, NRES and CEL of the thermal and hydro power plants in Bangladesh.

Year	RES (%)	NRES (%)	CEL (Petajoule)
2007–2008	1.64	98.36	159.6
2008–2009	0.67	99.33	159.9
2009–2010	1.10	98.90	186.7
2010–2011	1.23	98.77	198.8
2011–2012	1.00	99.00	216.0
2012–2013	1.06	98.04	231.3
2013–2014	0.67	99.33	241.9
2014–2015	0.62	99.38	252.9
2015–2016	0.90	99.10	295.7

NRES was higher in that year (99.4%). From Table 11 it can also be seen that CEL is increasing and attained a peak value of 295.7 petajoules in 2015–2016. The largest loss is from thermal power plants is due to higher irreversibility associated with these plants. In order to lower CEL, energy production from sustainable energy sources such as solar, wind, hydro and biomass should be the main priority. Inclusion of renewable energy sources will increase RES and decrease NRES. If RES is increased, fossil fuel depletion will decrease and SI will increase.

## 6. Conclusions

Energy, exergy and sustainability analyses are performed of Bangladesh's utility sector from 2007 to 2016. The overall energy efficiencies vary between 34.9% and 36.3% and the overall exergy efficiencies vary between 35.0% and 39.2% within this period. The

hydro power plant is found to be more exergy efficient than thermal power plants. Higher improvement potential is associated with thermal power plants. From the sustainability analyses, it is found that the utility sector is inefficient at utilizing fossil fuel. The ESI differs between 1.54 and 1.64 and RI and LOP are higher for the gas operated power plants. The WER varies between 0.48 and 0.59 while the EEF varies between 1.35 and 1.68. The non-renewable exergy shares are significantly higher than the renewable exergy share. The cumulative exergy loss is increasing and a major portion of the input exergy is lost to the environment.

For sustainable energy generation and energy conservation, the Government of Bangladesh should adopt proper policies. The country should look forward to developing policies regarding the power generation sector. Modern equipment should be used for power generation. Old power plants should be properly re-designed and maintained to reduce losses. Special considerations should be given for gas operated power plants. Modern energy saving technologies and control systems should be given priority to reduce loss. Selection of appropriate sites for installation of power plants may reduce distribution and transmission loss.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Shahariar Hossain:** Conceptualization, Formal analysis, Methodology, Draft. **Hemal Chowdhury:** Conceptualization, Formal analysis, Methodology, Draft. **Tamal Chowdhury:** Conceptualization, Formal analysis, Methodology, Draft. **Jamal Uddin Ahamed:** Data collection, Validation. **R. Saidur:** Review, Editing, Writing. **Sadiq M. Sait:** Review, Editing, Writing. **Marc A. Rosen:** Review, Editing, Writing.

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