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Research Article

Municipal Solid Waste to Energy Generation in Bangladesh: Possible Scenarios to Generate Renewable Electricity in Dhaka and Chittagong City

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Increased generation of methane (CH_4) from municipal solid wastes (MSW) alarms the world to take proper initiative for the sustainable management of MSW, because it is 34 times stronger than carbon dioxide (CO_2). Mounting land scarcity issue around the world brands the waste to energy (WtE) strategy for MSW management in urban areas as a promising option, because WtE not only reduces the land pressure problem, but also generates electricity, heat, and green jobs. The goal of this study is to evaluate the renewable electricity generation potential and associated carbon reduction of MSW management in Bangladesh using WtE strategies. The study is conducted in two major cities of Bangladesh: Dhaka and Chittagong. Six different WtE scenarios are evaluated consisting of mixed MSW incineration and landfill gas (LFG) recovery system. Energy potential of different WtE strategy is assessed using standard energy conversion model and subsequent GHGs emissions models. Scenario A_1 results in highest economic and energy potential and net negative GHGs emission. Sensitivity analysis by varying MSW moisture content reveals higher energy potential and less GHGs emissions from MSW possessing low moisture content. The study proposes mixed MSW incineration that could be a potential WtE strategy for renewable electricity generation in Bangladesh.

1. Introduction

The agitated race of human society towards modern urban life around the world generates tremendous amount of municipal solid waste (MSW) [1], because the generation rate is mounting even faster than the rate of urbanization [2]. Global MSW generation showed a twofold increase just only within 10 years from 0.68 billion tons per year in 2000 to 1.3 billion tons per year in 2010. Moreover, it is projected to reach 2.2 billion tons per year by 2025 and 4.2 billion tons per year by 2050 [2]. This humongous waste load of urbanized world if not managed properly will certainly have a negative impact on sustainable living style, local environment, and human health [3]. Severe MSW management problems are reported in a number of cities of different countries like China [4], India [5], Malaysia [6], Thailand [7], and Bangladesh [8], because of rapid population growth, fast industrialization, and urbanization.

Tremendous generation of MSW because of fast population growth and ongoing economic development is already blamed for significant environmental glitches in Bangladesh [8–10]. Bangladesh has enjoyed tremendous growth in its economy over the last few years, and this persuades a great influx of village workforce to cities [11–13]. In this circumstance, for sustainable MSW management population and economy growth should be constructively transformed, because they are the major drivers of wastes generation [6, 14]. Around the world to ensure sustainable MSW management, four options are now considered, such as thermal treatment, biological treatment, landfilling with energy recovery, and recycling [15], as presented in Figure 1. Among them, thermal treatment, biological treatment, and landfilling with energy recovery are based on the theme of energy recovery option of MSW management hierarchy [16].

Waste treatment process generating energy in the form of electricity, heat, or transport fuels is considered as waste to energy (WtE) option. Each year 2.3 billion tons of MSW will be generated by 2025, and this is equivalent to 2.58×10^{23} MJ of energy. So WtE is a very promising alternative energy option

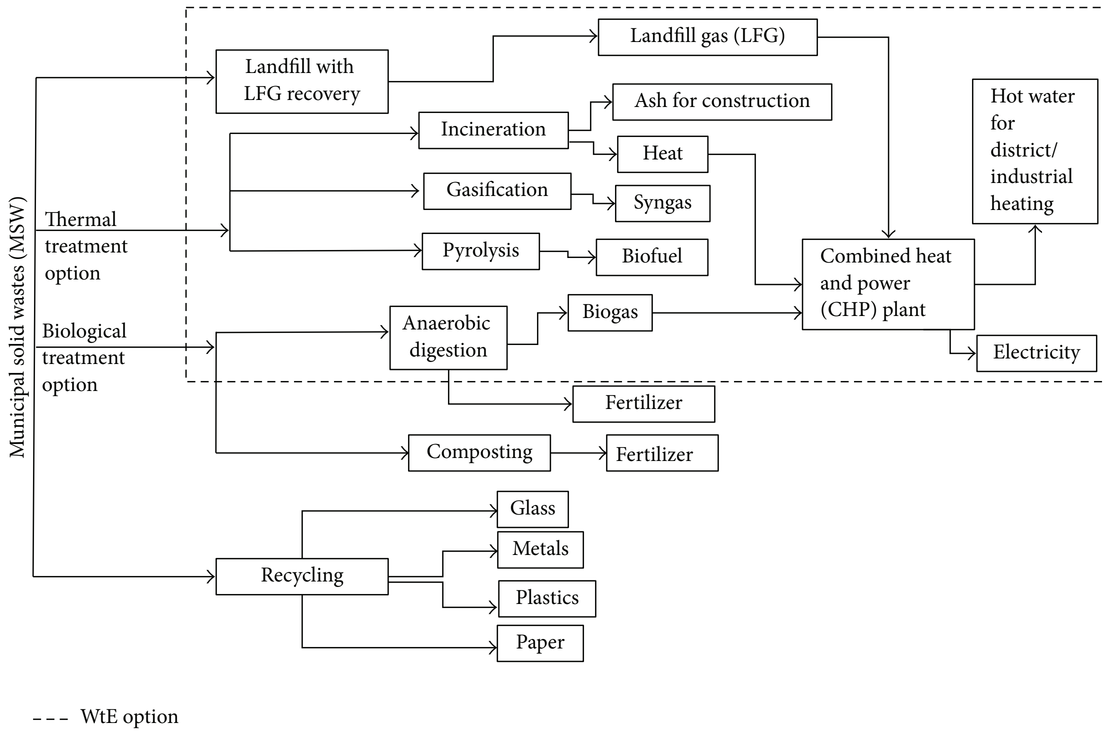


Figure 1: MSW management pathways with potential economic product generation.

for the future because with this amount of energy 10% of global annual electricity need can be satisfied [17]. In fact, by the world economic forum report "Green Investing: Towards a Clean Energy Infrastructure" published in 2009, WtE is identified as one of the eight technologies having significant potential to contribute to future low-carbon energy system [18]. According to some estimation, WtE option by 2022 will treat at least 261 million tons of MSW per year to produce 283 terawatt hours (TWh) of electricity and heat [17]. The most two common practices for WtE method are mixed MSW incineration and landfill gas (LFG) recovery system [19], but the most economically feasible solutions to be used in the future energy system are mixed MSW incineration [20]. A general overview of major WtE technologies is presented in Table 1.

Large-scale WtE option, mostly incineration of mixed MSW as a means of sustainable MSW management, has been implemented in the countries like Denmark, Germany, Netherlands, Sweden, and UK [20]; Malaysia [19]; Indonesia, China, Japan, and Korea [21]; and USA [22]. Globally more than 800 WtE incineration plants are now operating in approximately 40 countries. Most of them located in Europe (472), Japan (100), and USA (86) [23]. In China, operational or under construction WtE incineration plants are expected to be over 300 by the end of 2015 [4, 24], with the aim of building the world largest WtE incineration plant in Shenzhen [25].

On the other hand, sustainable MSW management in Bangladesh is still a dilemma in spite of continuous government effort [8, 9]. This has been reflected in the available scientific literature related with MSW management in Bangladesh. A number of studies have been conducted covering a number of aspects related with MSW management issues in Bangladesh, such as characterization and factor of the MSW generation [10, 26–29], disposal status and management problems [8, 30–35], peoples willingness to pay for different wastes management option [36, 37], composting aspects [26, 38, 39], and recycling aspects [33, 40]. A few studies have been conducted to estimate electricity generation potential [41–43], but none of the studies is conducted to comprehensively assess the feasibility of WtE strategies in terms of energy conversion and carbon reduction from MSW management in Bangladesh.

Energy availability greatly stimulates the economic and social development as well as living standard in a society [44, 45]. Bangladesh is an energy deficit country and the energy source is not sustainable because of the major share of fossil fuel in the energy mix [46, 47]. Moreover, to overcome this energy deficit situation, Bangladesh government recently aims to reduce gas-based electricity generation and gradually shift to coal-fired power plant, which will certainly increase national carbon footprint [48–50]. Bangladesh is an energy dependent country, and an increase in the energy supply has a positive impact on economic development [51–53]. In these circumstances, WtE for MSW management in Bangladesh can be a viable option for alternative and renewable electricity generation. Such strategy will also avoid significant GHG emissions by replacing the equivalent fossil fuels electricity. Moreover, deploying WtE strategy will help Bangladesh to move towards zero waste society and to adopt circular economy principle at the national level.

In view of the above-mentioned contexts, this study is conducted with the goal to assess the potential of WtE

Table 1: Overview of major WtE technologies.

WtE technology	Description	Conversion efficiency (MWh/ton MSW)	Service life (year)	Typical MSW input heating value (MJ/Kg)	Max fuel moisture (%)	Input	Products
Waste incineration	Mixed MSW incinerated in a boiler and equipped with CHP plant. Incineration temperatures usually between 1000 and 1200°C.	0.5[A]	30[A]	8–10.5[B]	40–50[A]	Mixed MSW	Electricity and heat.
Pyrolysis	Thermochemical decomposition of organic fraction of MSW at low temperatures in the presence of limited oxygen or in the absence of oxygen. Operating temperatures usually between 200 and 300°C.	0.3[A]	20[A]		10[A]	Sorted MSW	Liquid oil, char, and gas.
Gasification	Process of reacting the organic fraction of MSW at high temperatures with controlled amount of oxygen and steam to produce carbon monoxide, hydrogen, and carbon dioxide. Operating temperature is >700°C.	0.9[A]	20[A]	16.5[B]	40–50[A]	Sorted MSW	Electricity, CH_4, hydrogen, and ethanol.
Anaerobic digestion	Biological process of breakdown of organic fraction of MSW by a consortium of anaerobic microorganisms working synergistically in an oxygen poor environment. Most of the anaerobic digesters are designed to operate in the temperature range of 30–35°C.	0.15[D]	20[A]	2.5[B]	Approx. 97[A]	Sorted MSW	Electricity, heat, and LNG.
LFG gas recovery	Landfill gas (LFG) is a saturated gas consisting of 50% CH_4 and 50% CO_2 by volume, along with some other trace contaminants. CH_4 is trapped to generate electricity.	0.23[E]	30 to 50[E]	—	70–80[C]	Mixed or sorted MSW	Electricity, heat, and LNG.

Note: [A][56], [B][20], [C][57], [D][58], and [E][6].

Table 2: MSW disposal site and their salient features in Dhaka and Chittagong city.

Salient features	Dhaka		Chittagong			
	Matuail	Amin Bazar	Ananda Bazar	Arefin Nagar	Kalurghat	Roufabad
Area (hectares)	40	20	2.023	29.5	7.28	2.83
Condition	In operation	In operation	In operation	In operation	In operation	Closed
Land filling started	2003	2007	1960	2011	2015	2001
Height of MSW deposit (meter)	7	6.4	13.7	6.5	6	9
Distance from the city (km)	6	8	6	5	7	5
Closed/expected end of life	2021	2023	2020	2017	2016	2014
Average disposal per day (tons)	2000	1200	350	671	722	950
Current CH_4 status	No recovery	No recovery	No recovery	No recovery	No recovery	No recovery
Ward covered	55	36	21	20	21	28

strategy for renewable electricity generation from MSW and associated fossil fuel carbon avoidance in Bangladesh. Dhaka and Chittagong are taken as the study location, because these two are the most crowded and strategically important cities of Bangladesh. Dhaka is the capital, while Chittagong is considered as the commercial capital of Bangladesh. Two WtE technologies, such as mixed MSW incineration and LFG recovery, are selected for the assessment of renewable energy generation and carbon reduction, because these two options are the most preferable and mature technologies practicing around the world.

2. Existing MSW Management in Dhaka and Chittagong

Under the ministry of local government and engineering department in each major city or municipality, city corporation or municipalities are responsible authority for management of MSW in Bangladesh. Dhaka City Corporation (DCC) was responsible for the collection, transportation, and disposal of MSW in Dhaka city with 92 administrative area named wards. But now, DCC is divided into DCC (North) with 36 wards and DCC (South) with 56 wards. The collection, transportation, and disposal of MSW in Dhaka city are also divided accordingly [54]. Similarly, Chittagong City Corporation (CCC) is responsible for the collection, transportation, and disposal of MSW in Chittagong city with 41 wards. All the MSW are disposed in the open dump sites after collecting from household or large wastes container in Dhaka and Chittagong city [30, 31, 55]. The typical features of open dump sites in Dhaka and Chittagong city are presented in Table 2. In Dhaka all the wastes are sent for open dumping in Matuail and Amin Bazar dumping ground. Matuail dumping sites are named as sanitary landfill, but now open dumping is practiced here (Figures 2(c) and 2(d)). Wastes from 55 wards in Dhaka city are dumped in Matuail dumping sites, and wastes from 36 wards are dumped in Amin Bazar open dumping site. In Chittagong, all the wastes are currently dumped into Ananda Bazar, Kalurghat, and Arefin Nagar open dumping sites, while Roufabad open dumping site closed in 2014. Ananda Bazar dumping ground is the oldest open dumping sites in Chittagong and expected to close in 2020.

Table 3: Typical MSW characteristics of Dhaka and Chittagong city.

Material	Dhaka				Chittagong			
	Weight%							
	A	B	C	D	A	E	F	G
Food/organic	68.3	84.37	80	59.91	73.7	61	72	62
Plastic	4.3	1.74	4.5	—	2.8	3	3	2
Paper	10.7	5.68	10	11.21	10	9	5	3
Textile	—	1.83	—	—	—	8	3	1
Wood	—	—	—	—	—	—	2	3
Grass/garden wastes	—	—	—	8.76	—	3	—	—
Rubber	—	—	—	—	—	—	—	—
Glass	0.7	6.38	1.7	—	0.9	3	3	5
Aluminum/metals	2.0	—	1	0.15	2.2	2	4	9
Textile and wood	2.2	—	—	—	2.1	—	3	—
Leather and rubber	1.4	—	—	17.67	1	—	—	—
Pack	—	—					6	9
Stone/rocks	—	—	—	2.30	—	5	2	6
Others/miscellaneous	10.4	—	3.5	—	7.4	6	—	—

Note. [A]Same MSW character of Dhaka and Chittagong city is reported in these studies [26, 40, 59].
[B][43], [C][29], [D][41], [E][31], [F][27], and [G][28].

Typical characterization of MSW in Dhaka and Chittagong city by different study is presented in Table 3. From Table 3, it can be clearly stated that the solid wastes of Dhaka and Chittagong consist of mainly organic and inorganic fraction like food waste, paper, textile, rubber, plastic, glass, metals, and wood. The major fraction (75%) of MSW in Bangladesh is food waste [28, 31], whereas it is 50% in China [4], 40% to 60% in Malaysia [6, 44], and 20% to 30% in US and European countries [42].

3. Methodology

3.1. Data Collection. The field work of this study was conducted in Dhaka city and Chittagong city (Figure 3) for a total time period of five months. Detailed survey was conducted during this period by a group of data collectors. Detailed survey covers basically direct observations, interviewing the officials of MSW management authority of both cities, and

Figure 2: MSW disposal site in Dhaka and Chittagong city. (a-b) Amin Bazar and (c-d) Matuail dumping site in Dhaka; Matuail open dumping sites named as sanitary landfill (red circle in (d)), with the aim of converting it to sanitary landfill site in the future, but open dumping is practiced now. Kalurghat open dumping sites (e-f) and Ananda Bazar open dumping sites (g–i) in Chittagong.

segregation of MSW at the solid waste disposal sites (SWDS). Segregation of MSW was performed at the primary level (source), secondary level (dustbin along the street), and third level (SWDS) to identify and quantify different MSW categories. Quantification and percentage of different MSW were computed from 5 kg sample. MSW generation and disposal data for both the cities from 2000 till 2015 were collected from authority of both the cities. An extensive literature review was also performed to compare the composition and characteristic of MSW of both cities. MSW projection models through (1) and (2) were used to predict the future MSW in Dhaka and Chittagong city (Section 3.2), (6) and (7) were used to model the energy generation through MSW incineration plant (Section 3.4), and (8) were used to model the CH_4 emissions from landfill (Section 3.4). Equations (10) and (11) were used to model the net carbon emission (Sections 3.6 and 3.7).

Different WtE options were analyzed under six different scenarios to find the optimum solution. A sensitivity analysis was performed to evaluate the effects of moisture content of MSW on the energy potential and GHGs emissions. The methodological framework of the study is presented in Figure 4.

3.2. Projected Future MSW Generation. Future MSW generation was projected for Dhaka and Chittagong city using (1) and (2). A brief sketch about these two approaches is given here:

(i) Historical trend: annual growth rate of population in the respective city was computed from census data [62], and average growth rate in the per capita waste generation was computed from historical waste generation (2001 to 2015). Projected waste generation was calculated using

$$\text{PWG} = \frac{(\text{PBY} + \text{PBY} \times \text{AGP}) \times (\text{PCWB} + \text{PCWB} \times \text{AGW}) \times 365 \times 1}{1000}. \quad (1)$$

Here, PWG is projected wastes generation in a year (tons); PBY is population in baseline year; AGP is annual growth rate of population; PCWB is per capita wastes generation in baseline year (kg/cap/day); AGW is average growth rate in the per capita waste generation.

(ii) Compound annual growth rate (CAGR), gross annual product (GAP), and income spending approach:

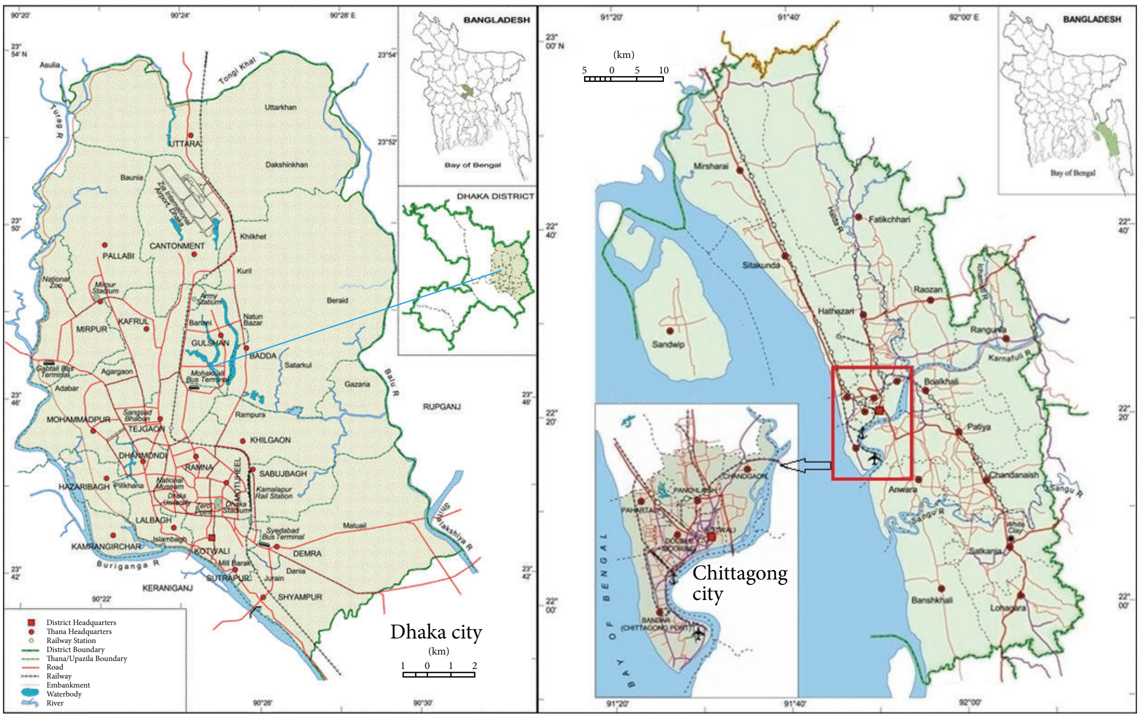


Figure 3: Generalized map of the studied city of Bangladesh and its location in Bangladesh.

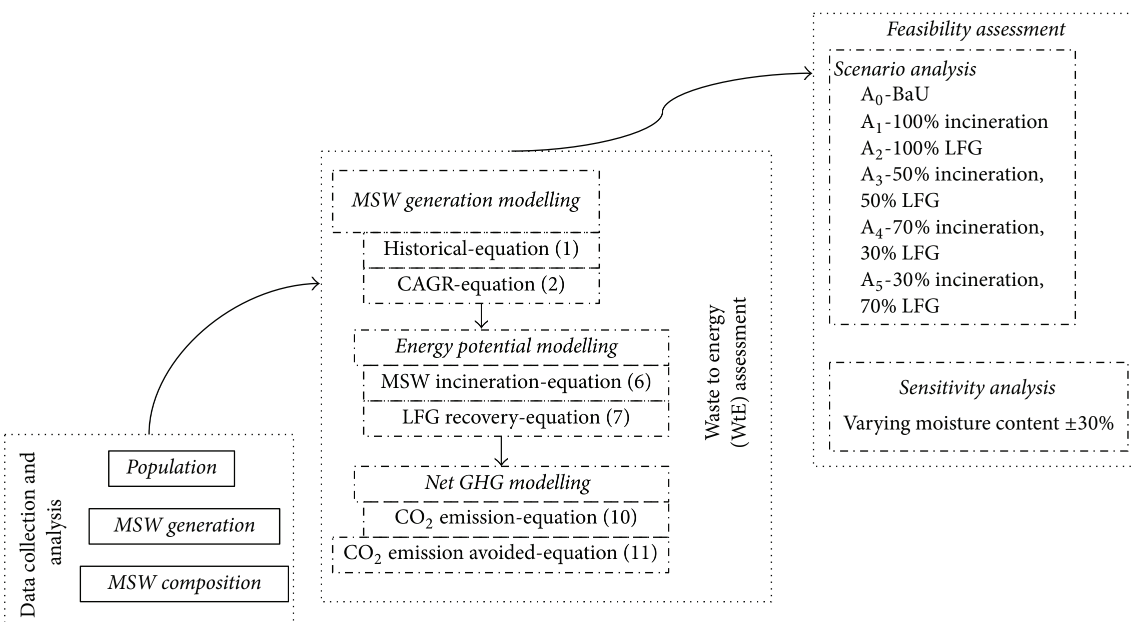


Figure 4: Methodological approach of the study.

compound annual growth rate (CAGR) of population in the respective city was calculated at first using census data [62]. Gross annual product (GAP) growth rate of Bangladesh was assumed as 4%, and 70% of income is assumed to be used for expenditure to bear the personal consumption in Bangladesh [30]. Waste generation growth factor is calculated as 0.028 (4%× 70%). Projected waste generation was calculated using

$$\mathrm{PWG} = \frac{(\mathrm{PBY} + \mathrm{PBY} \times \mathrm{CAGR}) \times (\mathrm{PCWB} + \mathrm{PCWB} \times \mathrm{WGG}) \times 365 \times 1}{1000}. \quad (2)$$

Here, PWG is projected wastes generation in a year (tons). PBY is population in baseline year. CAGR is compound annual growth rate of population. PCWB is per capita wastes generation in baseline year (kg/cap/day). WGG is waste generation growth factor.

3.3. MSW Physical and Chemical Properties. Physical characteristics of the MSW stream, like waste composition fraction on wet weight basis, dry weight fraction, and moisture content, are critical factors to determine energy recovery alternative. Similarly, chemical properties, such as organic carbon (C_{org}), inorganic carbon (C_{iorg}), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), and ash content of MSW, also influence this decision [19]. Physical characteristics of MSW stream of Dhaka and Chittagong city were determined by segregating the solid wastes at the primary level (source), secondary level (dustbin along the street), and third level (SWDS). Quantification and percentage of different solid wastes were calculated from 5 kg sample. Standard molecular composition of different solid wastes category based on dry weight fraction of MSW was used in this study [60]. Moisture content (%) and dry weight fraction (%) of MSW were calculated using (3) and (4). Wet weight fraction (%) of MSW of Dhaka and Chittagong city was rounded off to the nearest whole number.

$$X = \left(\frac{A - B}{A}\right) \times 100. \tag{3}$$

In (3), X is moisture fraction of MSW (%), A is initial weight of the sample which belongs to an individual class, and B is weight of an individual class after drying.

$$X = Y \times (100 - Z). \tag{4}$$

In (4), X is dry weight fraction of MSW (%), Y is wet weight fraction of MSW (%), and Z is moisture content (%). The physical and chemical characteristics of the MSW of Dhaka and Chittagong city are presented in Table 4.

3.4. Energy from MSW by Waste Incineration. Energy content of MSW highly influences the waste combustion processes in an incinerator to generate the electricity. For generation of electricity by combusting MSW, unsegregated wastes feed stock combusted in a furnace or boiler, under high temperature (980 to 1090°C) conditions with excess oxygen. MSW feed stock is converted into heat, flue gases and particulates, and incinerator bottom ash. The heat is used to produce steam and based on the Rankine cycle principle in steam turbine electricity is generated [19, 60, 61]. Under ideal situation MSW combustion processes chemical reaction is represented using [19]

$$\text{Organic matter} + \text{Excess air} = CO_2 + H_2O + O_2 + N_2 + \text{Ash} + \text{Heat}. \tag{5}$$

The energy content of MSW is usually expressed by its lower heating value (LHV). In this study, the approximate LHV of MSW of Dhaka and Chittagong city is computed by ultimate analysis and compositional analysis. Under the ultimate analysis, LHV of MSW of Dhaka and Chittagong city was estimated using the mathematical correlation of the modified Dulong equation, as shown in (6) [19, 60].

Under the compositional analysis, LHV of MSW of Dhaka and Chittagong city was estimated using the typical heat values of MSW components and using (7). Typical heat values of MSW components are presented in Table 5 [61].

$$\text{Energy content (LHV in kcal/kg)} = \Big\{7831X_{C_{org}} + 35932\left(X_{H_2} - \frac{X_{O_2}}{18}\right) + 2212X_S + 354X_{C_{iorg}} + 1187X_{O_2} + 578X_{N_2}\Big\} \times (100 - MC). \tag{6}$$

The values of the variables in (6), such as C_{org}, C_{iorg}, and MC (moisture content), are presented in Table 4.

$$\text{Energy content (LHV in KJ/Kg)} = \sum_j HV_j \times DW_j. \tag{7}$$

In (7), HV_j is typical heat values of MSW component j and DW_j is dry weight fraction (%) of component j.

3.5. CH_4 Generation in Landfill. Estimation of methane (CH_4) emission from SWDS was done using a simple and straightforward method called the intergovernmental panel on climate change (IPCC) methodology [63]. The global warming potential (GWP) of CH_4 was taken as 34 [64]. Methane emission from SWDS was estimated using (8), and adopted parameters are presented in Table 6.

$$CH_4 \text{ emission (tones/year)} = (MSW \times MSWF \times MCF \times DOC \times DOCF \times FM \times X - RM)(1 - OF). \tag{8}$$

In (8), MSW is total waste generation (tones/year); MSWF is waste fraction disposed to SWDS; X is 16/12, a conversion factor for converting C to CH_4. The following are several coefficients involved to adopt the IPCC model to estimate the CH_4 emission for this study.

(a) MSWF (wastes fraction disposed to landfills): all of the total MSW generated in Bangladesh is sent to the open dumping SWDS [30, 31, 55]. During the field visit of this study, this was also revealed and presented in Table 4. So, MSWF was taken as 1.

(b) MCF (methane correction factor): the MCF is coefficient for different types of SWDS. For properly managed sanitary landfills, MCF = 1; for uncategorized SWDS, MCF = 0.6; for open dump with >5 m waste height, MCF = 0.8; and for open dump with <5 m waste height, MCF = 0.4 [44, 63, 65]. As reported in Table 4 all the existing open dumping SWDS in Dhaka and Chittagong are of height greater than 5 m, so MCF value was taken as 0.8.

Table 4: Physical and chemical properties of MSW of Dhaka and Chittagong city considered in this study.

			Food wastes	Plastic	Paper	Grass & straw	Glass & ceramic	Metals	Textiles	Others
Physical properties	Dhaka	Wet weight fraction (%)	80	2	8	2	1	1	—	6
		Moisture content (%)	72.34	0.53	3.2	38.21	0	0	—	8.67
		Dry weight fraction (%)	22.13	1.99	7.74	1.24	1.00	1.00	—	5.48
Physical properties	Chittagong	Wet weight fraction (%)	70	5	10	2	1	4	5	3
		Moisture content (%)	74.86	0.61	3.60	34.18	0	0	7.3	7.24
		Dry weight fraction (%)	17.60	4.97	9.64	1.32	1.00	4.00	4.64	2.78
Chemical properties[a]	Dhaka and Chittagong	Organic carbon (C_{org}, %)	48.00	0	43.50	47.8	0	0	55.00	24.3
		Inorganic carbon (C_{iorg}, %)	0	60.00	0	0	0.50	4.50	0	0
		Ash (%)	5.00	10.0	6.00	4.50	98.90	0.46	2.50	68
		Sulphur (S, %),	2.60	0.00	0.30	3.40	0.10	0	90.50	0.2
		Nitrogen (N, %),	0.40	0.10	0.20	0.30	0.00	0	0.10	0.5
		Oxygen (O, %),	37.60	7.20	44.00	38.00	0.40	4.30	31.20	4
		Hydrogen (H, %)	6.40	22.80	6.00	6.00	0.10	0.60	6.60	3

Note: [a]standard molecular composition of MSW [60].

Table 5: Typical heat values of MSW components considered in this study [61].

MSW components	Heat value[a] (KJ/Kg, dry weight)
Food waste	957.13
Paper	3445.68
Plastics	6699.94
Textiles	3589.25
Glass and ceramic	28.71
Metals	143.57
Grass and straw	1339.99
Others	1435.70

Note: [a]the values are converted from Btu/lb dry weight to KJ/Kg dry weight.

Table 6: Parameters adopted for IPCC default method in this study.

Parameter	Dhaka	Chittagong
MSWF	1	1
MCF	0.8	0.8
DOC	0.158	0.151
DOCF	0.77	0.77
FM	0.5	0.5
RM	0	0
OF	0	0

(c) DOC (degradable organic carbon) and DOCF (dissimilated organic fraction): according to IPCC suggested methodology, DOC ranges from 0.08 to 0.21 and was estimated using (8).

$$\text{DOC} = 0.4P + 0.15K + 0.3W. \quad (9)$$

Here, P is fraction of papers in MSW, K is fraction of kitchen/food wastes in MSW, and W is fraction of straw in MSW. Again, the DOCF is needed because the biodegradation of DOC does not occur completely over a long period, so a default value 0.77 was considered [44, 57].

(d) FM (fraction of methane in LFG): the fraction of methane production from LFG was set as 0.50 for Dhaka and Chittagong.

(e) RM (recovered CH_4) and OF (oxidation factor): since no methane recovery takes place either in Dhaka or in Chittagong open dumping SWDS, RM is zero and oxidation factor (OF) was also taken as zero as per IPCC default value [63].

3.6. GHGs Emissions from Combustion. As represented in (8), MSW combustion principally converts chemical energy stored into it to thermal energy through the combustion processes at high temperatures of 980 to 1090°C [61]. Because the combustion of MSW for WtE project though CO_2 is emitted, it avoids the use of fossil fuels and the release of CH_4 from SWDS. This type of WtE project can also account for carbon credit, because combustion of MSW and associated electricity generation avoid CO_2 emission from fossil fuel [19, 66]. In this study, CO_2 emissions from WtE project under different scenarios analysis were estimated using

$$CO_2 \text{ emissions from WtE project } \left(\frac{tCO_2}{tMSW}\right) = \sum_j \left(WF_j C_{iorg_j} \times OF_j\right) \times Z. \quad (10)$$

In (10), WF_j is dry weight fraction of waste component j; C_{iorg_j} is anthropogenic carbon fraction of component j; OF_j is oxidation factor, with the default value of 1 for MSW; Z = C to CO_2 conversion factor, with the value of 44/12; and j is component of MSW incinerated.

3.7. GHGs Avoidance. This study quantified the GHGs avoidance from equivalent CO_2 emission avoidance from coal electricity. Bangladesh now is establishing all the coal based power plant to ensure constant supply of electricity in the future [48]. Hence, electricity generated using MSW in Dhaka and Chittagong city under different scenarios using WtE strategy was assumed to replace electricity generated from coal and so CO_2 emission avoidance was computed using

$$CO_2 \text{ avoidance } (tCO_2) = EP_{MSW} \times CF_{EC}. \quad (11)$$

In (11), EP_{MSW} is electricity production from MSW using WtE projects or LFG and CF_{EC} is carbon emission factor of per KWh electricity production from coal. Carbon emission factor of 1.001 kg CO_2/KWh was considered in this study [67].

4. Results and Discussion

4.1. MSW and GHG Emission Projection. The actual and projected waste generation (a) and associated GHGs emission (b) in Dhaka and Chittagong city from year 2001 to year 2050 are presented in Figure 5. The waste generation showed increasing trend from 1.04 million tons per year to 6.6 million tons per year from year 2000 to 2050 under CAGR approach in Dhaka city. The associated GHGs emission from untreated MSW also increased gradually from 0.86 million tons CO_2 equivalent to 5.5 million tons CO_2 equivalent. Similarly, GHGs emission from untreated MSW in Chittagong city showed gradual increasing trend from 0.18 million tons CO_2 equivalent to 2.9 million tons CO_2 equivalent, with the increasing waste generation from 0.23 million tons to 3.6 million tons under CAGR approach from year 2000 to 2050. In Dhaka city, from the generated MSW estimated 1.18 million tons and 1.4 million tons of CO_2 equivalent were emitted in 2010 and 2015, respectively, and projected to generate 2.8 million tons of CO_2 equivalent by 2030 and 5.5 million tons of CO_2 equivalent by 2050. On the other hand, as expected total estimated CO_2 equivalent emission for the mentioned year was lower because of less MSW generation in Chittagong. It can be inferring that in Dhaka and Chittagong city the increasing generation rate of MSW is leading the direct increment of GHGs emission.

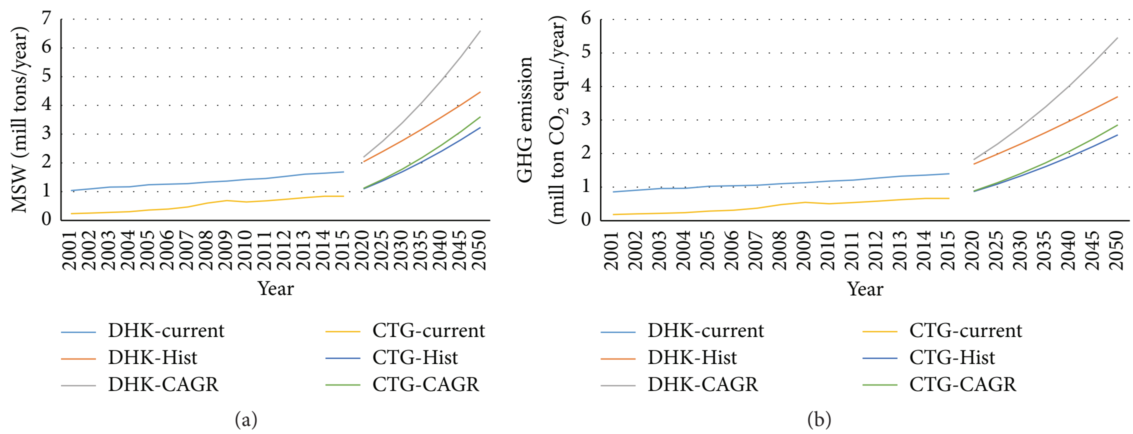


Figure 5: Actual and projected waste generation (a) and associated GHG emission (b) in Dhaka and Chittagong city. Actual wastes generation is from 2001 to 2015, and 2015 onwards represents projection. The legends of the figure are given at the bottom of (a) and (b).

Table 7: WtE analysis parameter adopted for this study.

Parameter	Value
MSW incineration	
LHV of MSW	
Ultimate analysis	6320 MJ/tMSW (Dhaka) 8440 MJ/tMSW (Chittagong)
Compositional analysis	710 MJ/tMSW (Dhaka) 1060 MJ/tMSW (Chittagong)
Heat recovery efficiency	80%
Electricity generation rate	1 MWh/15.65 GJ
Operating time	24 hours
Landfill	
CH_4 emissions	0.024 tCH_4/tMSW (Dhaka) 0.023 tCH_4/tMSW (Chittagong)
Methane GWP	34
CO_2 emission factor	0.827 tCO_2 equ./tMSW (Dhaka) 0.791 tCO_2 equ./tMSW (Chittagong)
CH_4 volume conversion factor	667 m^3/ton of CH_4
Calorific value of CH_4	17 MJ/m^3
Electricity generation factor	0.2775 KWh/MJ
Environmental and economic factor	
CO_2 emission factor for electricity	1.001 kg CO_2/KWh electricity
Carbon sequestered in forest area	1.22 ton of CO_2 sequestered per year/1 acre of forest
Carbon credit revenue	\$15.2/ton of CO_2
Electricity sales revenue	\$0.13/KWh of electricity consumed at the residential sector

4.2. WtE Analysis. The adopted WtE analysis parameters are presented in Table 7. The LHV of MSW of Dhaka and Chittagong city under the ultimate analysis was 6.32 MJ/kg and 8.44 MJ/kg, respectively. Under the compositional analysis, the LHV of MSW of Dhaka and Chittagong city was 0.71 MJ/kg and 1.06 MJ/kg, respectively. Ultimate analysis of MSW in both cities resulted in a higher LHV value. Heat recovery efficiency of mixed MSW incineration plant is reported as 80 to 90% [19, 68–70]. In this study, heat recovery efficiency of mixed MSW incineration plant in Dhaka and Chittagong city is assumed as 80%. Electricity generation rate of the incineration process using steam turbine was taken as 1 MWh/15.65 GJ heat [19]. CO_2 emissions due to mixed MSW incineration in Dhaka and Chittagong city were 0.046 tCO_2/tMSW and 0.12 tCO_2/tMSW, respectively. Landfill generated CH_4 is assumed to have a density of 0.667 kg/m^3, LHV of 17 MJ/m^3, and electricity generation factor of 0.2775 KWh/MJ [19, 44].

Figure 6 presents the energy potential through electricity generation from WtE strategy. As mentioned earlier, the

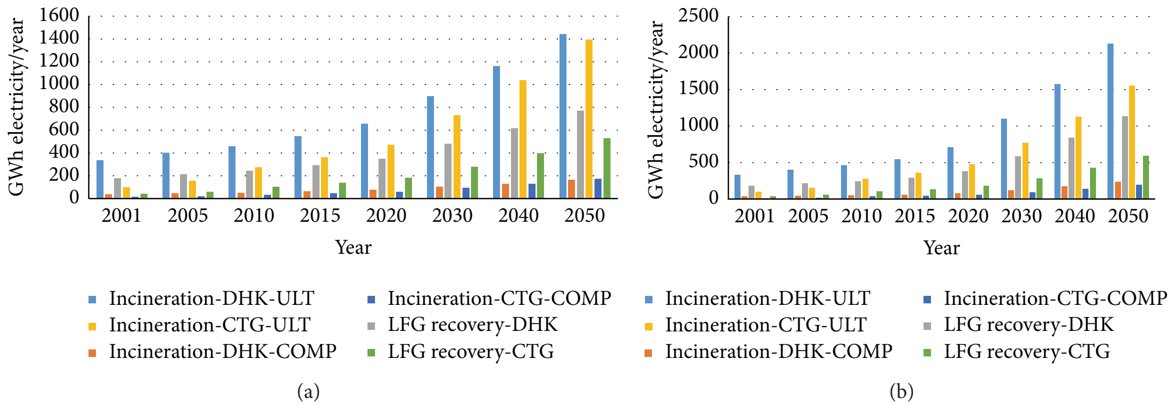


Figure 6: WtE assessments in terms of electricity generation potential (actual and projected) for Dhaka and Chittagong city from year 2001 to year 2050. (a) represents the projection using historical MSW generation rate and (b) represents the projection using CAGR approach. The legends of the figure are given at the bottom of (a) and (b).

energy of MSW in Dhaka and Chittagong city can be recovered through mixed MSW incineration plant and LFG recovery. As shown in Figure 6, the electricity generation from mixed MSW incineration and LFG recovery is estimated to increase from 2001 to 2050 because of increasing generation rate of MSW. In Dhaka and Chittagong city an estimated 1444 and 1394 GWh electricity can be produced, respectively, by 2050 through MSW incineration, under the context of ultimate analysis derived energy value and historical MSW generation rate. The electricity generation potential through MSW incineration was even higher when MSW was projected under CAGR approach, which was 2132 GWh for Dhaka and 1556 GWh for Chittagong. From WtE analysis, it was observed that MSW incineration has a higher electricity generation potential in both cities compared to LFG recovery. Other similar WtE potential assessment study also reported mass MSW incineration as highest power yielding option than the other WtE option like RDF and biomethanation and incineration with recycling [71] and LFG recovery [72].

4.3. Economic Analysis. The design capacity of mixed MSW incineration plant to generate electricity in Dhaka and Chittagong city is assumed as 1200 tons/day. The electricity generated is assumed to replace coal electricity in Bangladesh. Since the economic life of existing as well as proposed coal power plants in Bangladesh is assumed to be 30 to 50 years, for WtE incineration plant economic life was also taken as 35 years. For the economic analysis of this study, capital costs of incineration plant to generate electricity in Dhaka and Chittagong city are assumed as $36 per ton of MSW per day [73], and operation and maintenance costs as $60 per ton of MSW [74]. On the other hand, landfill with LFG recovery system is assumed to have a capacity of greater than 1000 tons mixed MSW/day for a period of 35 years.

For the economic analysis of this study, capital costs of landfill with LFGs recovery system in Dhaka and Chittagong city are assumed as $14 per ton of MSW per day, and operation and maintenance costs as $10 per ton of MSW [74]. Carbon credit revenue is assumed as $15.2 per ton of CO_2 [75]. Electricity sales revenue is taken from the residential tariff rate ($0.13/KWh) of Dhaka Power Distribution Company Limited (DPDC), because the generated electricity is assumed to consume at the residential sector.

The economic analysis based on electricity sales, carbon credits, and the capital and operating cost for MSW incineration plant and LFG recovery in Dhaka and Chittagong city is shown in Figure 7. Higher electricity production from MSW incineration plant increased the revenue as a result of higher electricity sales and associated claiming of carbon credits due to higher avoidance of CO_2 from coal based power plant. Approximately US $535 million and US $251 million of revenue can be generated from the sales of electricity and claiming of carbon credits from MSW incineration and LFG recovery, respectively, in Dhaka and Chittagong city under the CAGR approach of MSW projection in 2050, while under the historical MSW generation rate based MSW projection resulted in US $412 million and US $188.92 million of revenue in Dhaka and Chittagong city in 2050. However, incineration requires higher capital and operating costs than LFG recovery system, and revenue from MSW incineration is much lower when the LHV value calculated by compositional analysis was used as shown in Figure 7.

4.4. Scenario Analysis

4.4.1. Energy Potential and Net GHG. Six scenarios with varying WtE strategies were chosen to evaluate the impacts of MSW utilization for energy conversion and GHGs emissions (Table 8). The scenario analysis was performed using the LHV value of MSW estimated by ultimate analysis. The scenario analysis results of energy potential and net GHGs emissions for different WtE strategy in Dhaka and Chittagong city are presented in Figure 8. The net GHGs emission for all scenarios ranged from −0.29 to 0.81 tCO_2 equivalent/tMSW. The negative value in net GHGs emission represents the idea that this respective strategy avoided more CO_2 than its process emission. With the same composition of MSW, the net GHGs emissions from LFG recovery system were noticeably higher than MSW incineration. BaU

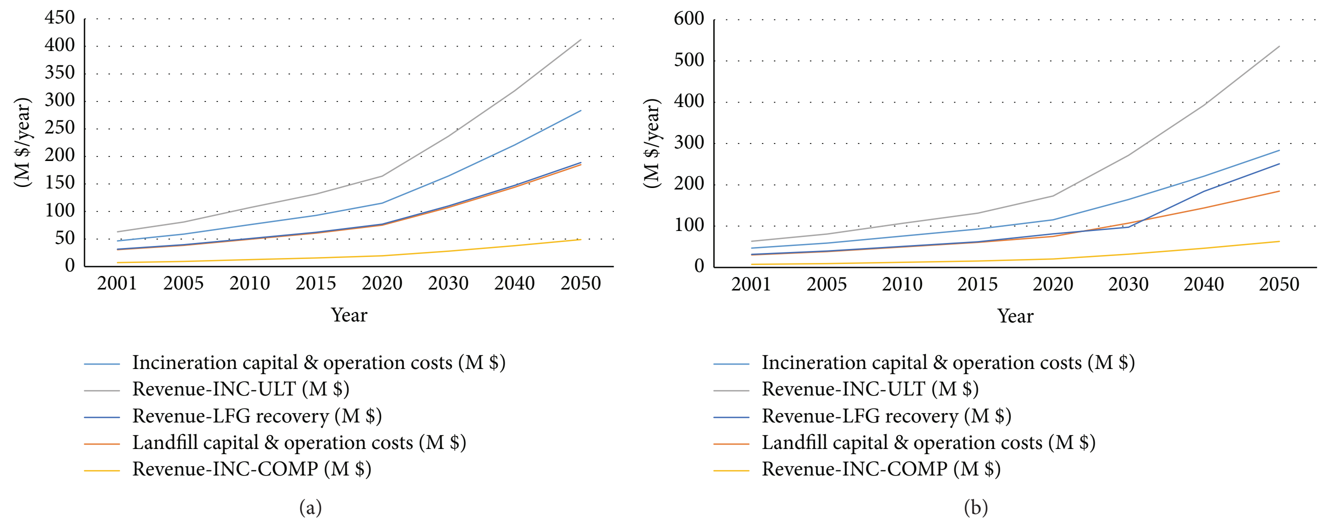


Figure 7: Economic analysis (actual and projected) for LFG recovery system and waste incineration in Dhaka and Chittagong from year 2000 to year 2050. Carbon credit and electricity sales summed as revenue. (a) represents the projection using historical MSW generation rate and (b) represents the projection using CAGR approach.

Table 8: Scenario description for the WtE option in Dhaka and Chittagong, Bangladesh.

Scenario	Description
Scenario A_0	Business as usual (BaU) scenario representing no WtE implementation.
Scenario A_1	All the MSW will be incinerated to generate electricity under the WtE project.
Scenario A_2	All the MSW will be landfilled to generate electricity from LFG, under the WtE project.
Scenario A_3	50% MSW will be incinerated and 50% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.
Scenario A_4	70% MSW will be incinerated and 30% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.
Scenario A_5	30% MSW will be incinerated and 70% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.

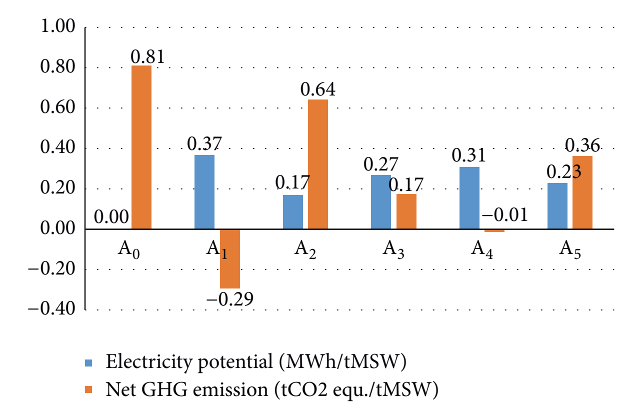


Figure 8: Energy potential and net GHG emissions of different WtE scenarios in Dhaka and Chittagong city, Bangladesh.

scenario was the worst one as expected, because of highest net GHG emission. Based on the analysis of this study, it is recommended that policy makers of Bangladesh can think about alternative MSW management based on WtE incineration plant for better environmental protection and higher economic benefit. Five alternative scenarios with WtE strategies were tested in this study with the aim of illustrating the policy makers of Bangladesh regarding the WtE potential of MSW. The results show that MSW mixed incineration has higher energy potential with even negative net GHGs emission. It can be said that mixed MSW incineration avoids more CO_2 than what it generates because of higher avoidance of coal generated electricity. Scenario A_1 was the best WtE strategy, generating 0.37 MWh/tMSW of electricity with −0.29 tCO_2 equivalent/tMSW of net GHGs emissions. When half of the MSW was incinerated and remaining half for LFG recovery system (scenario A_3), a total of 0.27 MWh/tMSW of electricity production and a moderate rate of net carbon emission (0.17 tCO_2 equivalent/tMSW) were observed. On the other hand, better performance (0.31 MWh/tMSW of electricity and −0.01 tCO_2 equivalent/tMSW of net GHGs emissions) was also observed in scenario A_4 compared to scenarios A_2, A_3, and A_5, where MSW incineration was the key strategy (70% MSW incineration and 30% LFG recovery system) for MSW management in Dhaka and Chittagong city.

4.4.2. Costs and Profit Analysis. No energy recovery is currently instigating in Dhaka and Chittagong city under BaU

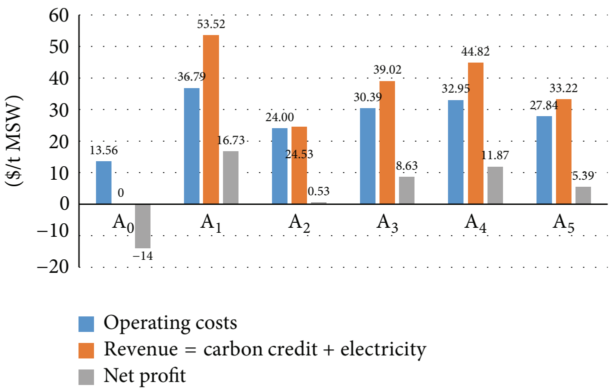
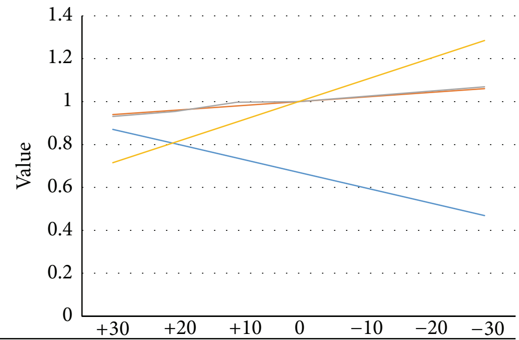


Figure 9: Costs and profit analysis of different WtE scenarios in Dhaka and Chittagong city, Bangladesh.



	+30	+20	+10	0	−10	−20	−30
Moisture content of MSW	0.871	0.804	0.737	0.67	0.603	0.536	0.469
Energy content	0.94	0.96	0.98	1	1.02	1.04	1.06
Electricity production	0.931	0.954	0.997	1	1.023	1.046	1.069
GHG emission	0.716	0.810	0.905	1	1.095	1.190	1.284

% change of moisture content

Figure 10: Sensitivity analysis of MSW moisture contents on WtE performance and GHG emission.

scenario (scenario A_0). So operating costs represent the current costs for managing (collection to disposal) the MSW in Dhaka and Chittagong city. In Dhaka, the operating costs for the ongoing MSW management practices are approximately BDT 626.24 ($7.97)/ton of MSW [1] and in Chittagong it is BDT 439 ($5.59)/ton of MSW [31]. Hence, these costs were considered as operating cost for BaU scenario (scenario A_0).

Figure 9 represents the cost and profit analysis of different WtE strategy for this study under different scenario. BaU scenario resulted in negative net profit as expected, because no effort is currently implemented in both cities to recover energy or generation of revenue from MSW. Scenario A_1 was the best WtE strategy with the highest profit of US $16.73/ton of MSW. Scenario A_1 can be considered as the optimal scenario, with the highest energy potential, best economic benefit, and GHGs emission reduction. The next best WtE strategy was scenario A_4, with the second highest profit of US $11.87/ton of MSW.

4.5. Sensitivity Analysis. To evaluate the impact of moisture content on overall energy potential and GHG emissions, a sensitivity analysis was performed by varying the moisture content of MSW within the range of ±0 to 30%. Scenario A_1 performance was evaluated, because it was identified as best option for WtE strategy for the management of MSW in Dhaka and Chittagong city, Bangladesh. The results of the sensitivity analysis varying the moisture content of MSW are presented in Figure 10. The results show that the overall GHG emission and energy generation were highly effected by the moisture content of MSW. With the increase or decrease of moisture content, the energy content, electricity generation, and GHGs emissions have changed reversely with a magnitude of 2%, 4.3%, and 9.5%, respectively. So it can be said that preheating of MSW to reduce the moisture content will increase the energy potential in Dhaka and Chittagong city and also reduce GHGs emissions.

5. Future Direction

This study is an attempt to inform the policy maker of Bangladesh regarding the potentiality of MSW as renewable source of energy in two megacities of Bangladesh, namely, Dhaka and Chittagong. Increasing demand for energy and unsustainable MSW management along with ever-growing shortage of available land space have necessitated the need for formulating a national WtE strategy. Bangladesh is trying to diversify its energy base by deploying a broad energy mix. On the other hand, energy security issue is one of the four security issues addressed in "National Adaptation Action Plan to Climate Change (NAPA), 2009" [76]. In spite of growing concern regarding energy security, Bangladesh is still not stepping forward for the expansion of renewable energy technologies and yet relying on merely fossil fuel resources, with the small target to generate 5% and 10% of electricity using renewable energy technologies by 2015 and 2020, respectively [77]. This study senses the urgency of reforming this policy because of global concern on GHGs footprint from fossil fuels and MSW generation. In the submitted intended nationally determined contributions (INDCs) to the UNFCCC, Bangladesh stated a voluntary 5% GHGs emission reduction from industry, energy, and transport sectors by 2030. Today or tomorrow, developing countries like Bangladesh will be also under the strict regulation for GHGs emission reduction, due to uncertainty regarding climate sensitivity [78]. Two selected WtE technologies, such as mixed MSW incineration and LFG recovery, were evaluated in this study, based on MSW characteristics and generation. The selected WtE strategy has validated the prospects of mixed MSW incineration in Bangladesh to mitigate GHGs emissions and to generate considerable revenue from electricity sales and carbon credit.

6. Conclusion

Based on the recognized energy conversion model and net carbon emission model, the WtE analysis in Dhaka and Chittagong city has been performed focusing on potential electricity production, GHGs emissions avoidance, and higher economic profit. Six alternative scenarios for WtE in Dhaka and Chittagong city of Bangladesh were assessed. Scenario A_1 provided the highest net profit with better energy potential and net GHG emissions reduction. The total estimated economic profit in 2050 from two cities could be US $170.76 million and US $128.87 million, respectively, under the CAGR approach and historical rate of MSW projection for scenario A_1. The estimated economic profit US $170.76 million is about 10 times higher than the income of the financial year 2013-14 (US $16.45 million) of CCC [79] and about 4 times higher than the income of the financial year 2012-13 (US $40.82 million) of Dhaka South City Corporation (DSCC) [80].

Sensitivity analysis revealed that some sort of preheating of MSW to reduce moisture can boost the energy recovery as well as GHGs emission reduction for the selected WtE strategy in Dhaka and Chittagong city. WtE strategy for the management of MSW in Dhaka and Chittagong city is vital to initiate nationwide circular economy principle and industrial ecology concept. This WtE strategy will also ensure availability of cheaper and greener energy, which will certainly reduce the energy crisis problem to a certain extent and can generate green jobs. The economic life of the WtE plant is chosen considering the economic life the coal based power plant on the ground that electricity generated will replace coal electricity. However, shorter life span like 20 years or less may alter the economic perspective of the chosen WtE scenario. The study concludes that WtE strategy based on mixed MSW incineration to generate electricity will deliver environmental benefits nationally and globally and will warrant comprehensive MSW management for the sustainable development in Bangladesh.

Abbreviations

CCC: Chittagong City Corporation
DCC: Dhaka City Corporation
DSCC: Dhaka South City Corporation
GHGs: Greenhouse gases
LFG: Landfill gas
LHV: Lower heating value
MSW: Municipal solid waste
SWDS: Solid waste disposal sites
WtE: Waste to energy.

Competing Interests

The author declares that there are no competing interests regarding the publication of this paper.

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