POTENTIAL OF WASTE TO ENERGY IN DHAKA CITY

SEPTEMBER 6, 2020

BANGLADESH POWER MANAGEMENT INSTITUTE (BPMI)
Power Division, Ministry of Power Energy and Mineral Resources

Research Report
On
"POTENTIAL OF WASTE TO ENERGY IN DHAKA CITY"

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Submission Date

6th September, 2020

Executive Summary:

The following report describes the results of a study on waste to energy conversion for the Dhaka City region of Bangladesh. Dhaka City is characterized by a high population growth rate [48]. Currently 20,284,000 permanent/temporary residents live in the area [49]. According to the recent development the population growth rate can be estimated as 3.61% per annum [49].

Many industrial branches provide a large number of jobs. First of all the garment industry dominates the industrial sector of the area and generates a large amount of specific waste. As the growth rate of the population in Dhaka has been high during recent years, the amount of waste generation in Dhaka is increasing. According to some sources, waste can be categorized as a) domestic waste, b) commercial waste, c) institutional waste, d) industrial waste, e) street sweepings, f) clinical waste and g) construction and demolition waste. The contributions of different sectors to the total generation of Dhaka city, where nearly 76% of generated waste came from the residential sector, 22% came from the commercial sector, 1% from the institutional sector and rest from other sectors [50].

The Dhaka City Cooperation estimated that, of the total daily generation of 3500 tons of solid waste, 1800 tons are collected and dumped by the city corporation, 900 tons go to backyard and land filling, 400 tons go to road side and open space, 300 tons are recycled by the street boys (mostly the children of slum dwellers), and 100 tons are recycled at the generation point. In a study by, it has been found that during wet season the waste generation rate increases by 46% [50]. 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 proposes mixed MSW incineration that could be a potential WtE strategy for renewable electricity generation in Bangladesh.

Acknowledgement:

Firstly, all the praise is paid to the Almighty, the most kind Allah for keeping us alive and able, giving us the knowledge, ability to think and for helping us to successfully finish the report, with His inexhaustible kindness.

We are highly indebted to Engr. Md. Mahbubur Rahman, Chief Engineer, IPP Cell, Bangladesh Power Development Board (BPDB) for his guidance and constant supervision as well as for providing necessary information regarding the research & also for his support in completing this research though he had busy schedules.

Lastly, thanks and appreciation are also extended to honorable rector, director and other respected officials of Bangladesh Power Management Institute (BPMI) for providing us with the opportunity of performing our research on such an important topic and making necessary arrangements for carrying out the research successfully.

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1. Introduction:

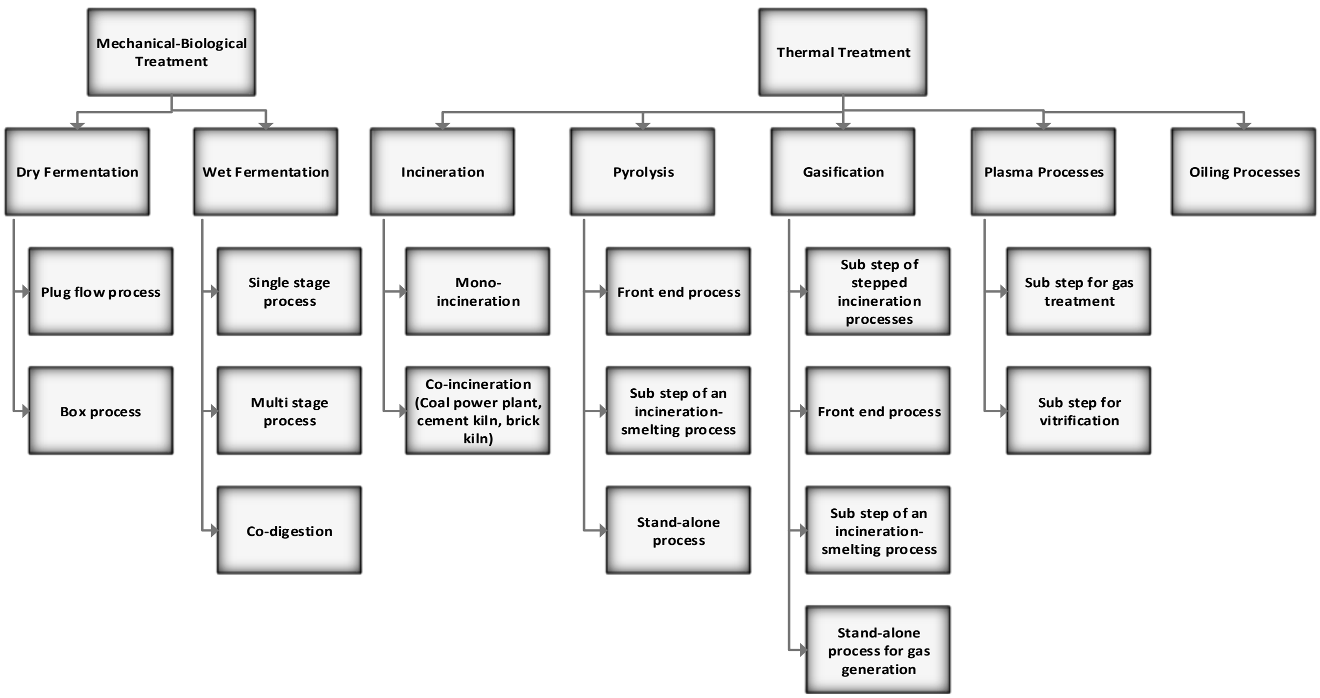
Dhaka is the most densely populated city of Bangladesh. At present 52,920 People live per square km in Dhaka [53]. According to the annual report of Dhaka north city Corporation A total of 4220 Metric ton of waste is generated each day under the 54 Wards of north city Corporation. For Dhaka South City Corporation the amount is 5610 Metric ton per day [51,52]. On the other hand, demand for electricity in Dhaka city is increasing fast. According to the Bangladesh economic review 2019 DPDC supply's 14.4% of the total electricity demand whereas DESCO supply's 8.7% of the total electricity consumed in the country. So in total Dhaka city consumes 25% of the total electricity generated in the country. BPDB expects the demand for electricity in Dhaka to increase annually by 10%. In such a scenario, electricity generation from waste presents a double opportunity for Dhaka City. In one way, the city will be able to get rid of its cumbersome waste, on the other hand the waste will contribute to the rising energy demand of the city. Waste treatment process generating energy in the form of electricity, heat, or transport fuels is considered as waste to energy (WtE) option. 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. This represent a greater opportunity for Bangladesh to achieve more success in SDG & PSMP implementation. Moreover, deploying WTE strategy will help Bangladesh to move towards zero waste society and to adopt circular economy principle at the national level. Different method can be put to practice with respect to WTE but from the context of Bangladesh Incineration, land fill gas seems to be the best possible alternative. Throughout the whole paper different aspects of WTE from Bangladesh context will be discussed along with the justification of these two methods.

2. Study Objectives

Huge amount of solid waste are produced in Dhaka city. Main objective of our study is to estimate how much energy we can produce from these waste based on energy availability from unit amount of waste. Steps those have been taken to produce energy from waste are discussed briefly. Future possibility of producing energy from MSW is also assessed. Based on collected framework data and information, and their subsequent assessment, potential of generation of energy from waste are discussed.

3. Overview of WtE-technologies

The promising and available WtE conversion technologies are thermal conversion methods (incineration, pyrolysis, and gasification), biochemical conversion, and landfill. Electricity, heat, fuel gases, liquids, and solids are the primary recovery products of those technologies.



Picture (1): Overview diagram an WtE-Technologies

3.1 Biological treatment

Biogas production processes are commonly divided into two main categories, according to the dry matter content in the process: Dry Anaerobic Digestion, and Wet Anaerobic Digestion. These processes can be applied as continuous feed or batch processes.

3.1.1 Dry digestion

Dry matter content in a Dry Digestion Plant is greater than 20%, usually 22-40%. Suitable biomaterials are grain straws, manure, and other organic wastes. The water content in the process is the main factor for process energy consumption. With lower water content, the dry process has lower energy consumption compared to wet process. Need for heating energy in wet processes is around 30% of total produced energy while dry process needs around 10% produced energy for heating. The water volume in the process has an effect also on the required reactor size, thus dry fermentation requires a smaller reactor [32].

3.1.1.1 Box digestion

In box digestion plants the reactor is loaded once and discharged until the end of the anaerobic process takes place. Batch reactors function similar to a landfill, but at higher temperatures and with continuous leachate recirculation the biogas yield is between 50 and 100 % higher than in landfills [33]

The concrete reactor with integrated heating system is loaded with organic waste by wheel-loaders and closed, starting the anaerobic degradation. During the decomposition, high organic content leachate is produced. The leachate is stored, heated and continuously redistributed in the reactor to increase the biogas yield. The produced biogas is utilized as fuel in a combined heat and power plant (CHP) for the production of heat and energy. The waste is kept in the reactor from 20 to 40 days, until the biogas production stops or drops [33]. The treated waste is then utilized to produce compost.

Regarding investment costs and its relatively simple technology this technology is the most favorable option for WtE under Bangladeshi conditions.

3.1.1.2 Plug flow digestion

A lot of biogas capacities installed in recent years use the plug flow technology. Central part of this technology is an elongated horizontal reactor. The specific of these reactors is the continuous radial stirring which lead to a plug flow of the fermentation substrate. Bypass flows are prevented with this technology. The fermentation substrate is moved along the whole length of the reactor before it is leaving the reactor [33]. Nevertheless, this technology has a slightly better energy efficiency. Though Investment costs are up to 10 % higher compared to the box digestion. [34]

3.1.2 Wet digestion

Conventional Wet Digestion Plants uses bio-slurries, which can be pumped and transferred via pipelines. Dry matter content of the bio-slurries are usually less than 15%. Biomaterial is usually diluted with a vast quantity of water to make it flow through pumps and prevent blockages in the pipelines. These wet digestion processes have a good history of usage, and the degree of process control is high in these plants [35].

3.1.2.1 Single stage process

In the single stage fermentation, the four anaerobic digestion steps take place in one reactor, i.e. they are not separated in time or in space. These types of plants have the advantages of being simple and easy to operate, and they require low investment costs.

The initial step is feeding the system with wet organic waste. Then the waste is sent to the pulper and mixed with process water, where the light fraction (plastics) and the heavy fraction (metals, stones and batteries) are removed. After this the hydrodynamic grit removal system separates the solids (glass fragments, grit, egg shells, gravel) from the liquids, producing a clean, homogenous pulp ready for digestion. The pulp is heated and enters the reactor where hydrolysis, acidogenesis, acetogenesis and methanogenesis take place. The digestor contents are continuously mixed using compressed biogas. The biogas is burned in a CHP to produce thermal and electrical energy, while the rest of the substrate is mechanically dewatered and sent to post-composting [37].

3.1.2.2 Multi stage process

In multi stage fermentation, two or more reactors are utilized to make the anaerobic digestion. [36]. The pulp extracted differs from the single stage process. In the multi stage the pulp is hygienized and centrifuged, obtaining from it two fractions, one is sent to hydrolysis and the other to methane reactor. A fraction with "a high amount of already dissolved organic material is pumped directly into the methane reactor. The dewatered solids are mixed with process water and fed into the hydrolysis reactor to dissolve the remaining organic solids. After 2-4 days, the suspension is dewatered and the resulting liquid also fed into the methane reactor", while the solids are sent to post-composting. The waste water resulting from the methane reactor is then treated by flocculation and denitrification [36].

3.1.2.3 Co-digestion

The Co-digestion was developed to improve the economy of the digestion of low organic substrates (slurry, sewage sludge) by adding of fat-rich substrates. Meanwhile a lot of substrate combinations were used to optimize the food resources for the bacteria and to balance the biogas generation. Economic effects and synergies can be achieved by the combination of co-digestion plants with existing wastewater treatment plants. The process technology of co-digestion is similar to wet digestion processes [36].

3.2 Thermal treatment

In general grate combustion is the common technique for the thermal treatment of household waste. For specific waste streams the fluidized bed combustion and the rotary kiln are in use. All other technologies are not state-of-the-art for household and commercial waste.

Certainly there are comparatively few examples worldwide where gasification or pyrolysis of household waste work reliable over a longer time on industrial scale.

3.2.1 Incineration

The incineration (combustion) of carbon-based materials in an oxygen-rich environment (greater than stoichiometric), typically at temperatures higher than 850°, produces a waste gas composed primarily of carbon dioxide (CO_2) and water (H_2O). Other air emissions are nitrogen oxides, Sulphur di-oxide, etc. The inorganic content of the waste is converted to ash. This is the most common and well-proven thermal process using a wide variety of fuels. During the full combustion there is oxygen in excess and, consequently, the stoichiometric coefficient of oxygen in the combustion reaction is higher than the value “1”. In theory, if the coefficient is equal to “1”, no carbon monoxide (CO) is produced and the average gas temperature is 1,200°C.

In the case of lack of oxygen, the reactions are characterized as incomplete combustion ones, where the produced CO2 reacts with C that has not been consumed yet and is converted to CO at higher temperatures.

The object of this thermal treatment method is the reduction of the volume of the treated waste with simultaneous utilization of the contained energy. The recovered energy could be used for:

- heating
- Steam production
- Electric energy production

The typical amount of net energy that can be produced per ton of domestic waste is about 0.7 MWh of electricity and 2 MWh of district heating. It can reduce the volume of the municipal solid waste by 90% and its weight by 75%. The incineration technology is viable for the thermal treatment of high quantities of solid waste (more than 100,000 tones per year) [38].

A number of preconditions have to be satisfied so that the complete combustion of the treated solid waste takes place:

- adequate fuel material and oxidation means at the combustion heart
- achievable ignition temperature
- suitable mixture proportion
- continuous removal of the gases that are produced during combustion
- continuous removal of the combustion residues
- maintenance of suitable temperature within the furnace
- turbulent flow of gases
- adequate residence time of waste at the combustion area [39].

3.2.2 Pyrolysis

Pyrolysis represents the thermal decomposition of organic materials by excluding gasification agents such as oxygen, air, carbon dioxide, steam, etc. Pyrolysis is the thermal degradation of carbon-based materials through the use of an indirect, external source of heat, typically at temperatures of 450° to 900°C, in the absence or almost complete absence of free oxygen. This drives off the volatile portions of the organic materials, resulting in a syngas composed primarily of H_2, CO, CO_2, CH_4 and complex hydrocarbons. The syngas can be utilized in boilers, gas turbines or internal combustion engines to generate electricity. Pyrolysis involves the thermal degradation of organic waste in the absence of free oxygen to produce a carbonaceous char, oils and combustible gases.

Although pyrolysis is an age-old technology, its application to biomass and waste materials is a relatively recent development. An alternative term for pyrolysis is thermolysis, which is technically more accurate for biomass energy processes because these systems are usually starved-air rather than the total absence of oxygen. Although all the products of pyrolysis may be useful, the main fuel for power generation is the pyrolysis oil. Depending on the process, this oil may be used as liquid fuel for burning in a boiler or as a substitute for diesel fuel in reciprocating engines, although this normally requires further processing [40].

The pyrolysis products can be liquid, solid and gaseous. The majority of the organic substances in waste are subjected to pyrolysis by 75 – 90 % into volatile substances and by 10 – 25 % to solid residue (coke). However, due to the existence of humidity and inorganic substances, the quantity of volatile substances varies from 60 to 70% and the coke between 30 and 40%

Solid	Carbon that is incorporated into several inert products	
Gas	CO, CO2, CH4, H2	700 m3 off-gases / tone of waste
Liquid	CH3COOH, CH3COCH3, CH3OH, complex oxygenised H/C	

Table 1. Brief description of the solid, liquid and gas products from the operation of a pyrolysis unit

3.2.2.1 Typical Pyrolysis Facility

In a typical pyrolysis facility the following are taking place:

- Drying of solid waste (100°-200°C)

- Initial decomposition of substances, initiation of the decomposition of H_2S and CO_2 (250°C)
- Break of the bonds of aliphatic substances – Start of the separation of CH_4 and other aliphatic substances (340°C).
- Enrichment of the produced material in carbon (380°C)
- Break of the bonds C – O and C - N (400°C).
- Conversion of coal tar materials into fuel material and tar (400° - 600°C).
- Decomposition to materials resistant to heat – Formation of aromatic substances (600°C).
- Production of aromatic substances, processes for hydrogen removal from organics like butadiene, etc. (>600°C)

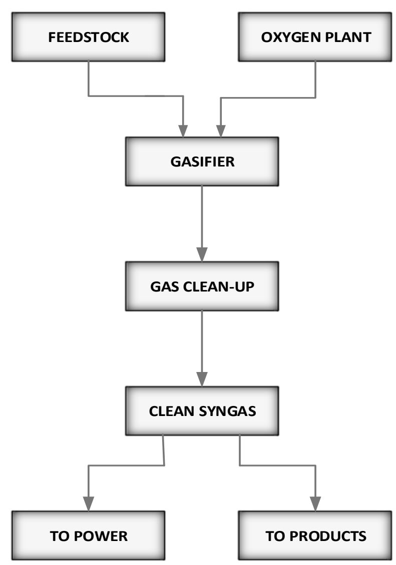
3.2.3 Gasification

Gasification refers to the conversion of carbon-containing materials at high temperatures into gaseous fuels. Gasification is differentiated from pyrolysis by the addition of reactive agents, which further convert carbonized residues into additional gaseous products. Gasification is, strictly speaking, the continuation of the pyrolysis process, where the residual carbon is oxidized from the glowing embers of the pyrolysis coke at temperatures above 800°C with sub stoichiometric oxygen. Steam, carbon dioxide, oxygen, or air are often used as gasification agents apart of the combustion process. The products generated in gasification process are determined by the type of agent used, e.g., lean gas, water gas, etc. The necessary reaction energy for the gasification process is generated by the partial combustion of the organic material inside the reactor. Analogous to pyrolysis a lack of information on operation experiences exist for the different gasification technologies. In particular long-term experiences are hardly available.

Gasification is defined as a thermal reaction with insufficient oxygen present for reaction of all hydrocarbons (compounds of carbon, hydrogen and oxygen molecules) to CO_2 and H_2O. This is a partial oxidation process which produces a composite gas (syngas) comprised primarily of hydrogen (H_2) and carbon monoxide (CO).

The major benefit of gasification of biowaste is that the product gas can be used directly, after significant cleaning, to fuel a gas turbine generator which itself will form part of a Combined Heat and Power (CHP) or Combined-Cycle Gas Turbine system, thus theoretically improving the overall thermal efficiency of the plant. The main disadvantage is that there can be more items of large equipment and the capital investment is correspondingly higher [41].

A typical gasification plant scheme is as given below:



Picture: Gasification Plant Scheme

Gasification and pyrolysis are suitable for the following specific cases of application:

- use in front of incineration processes (e.g. coal power plants, cement kilns) which can handle an uncleaned raw gas to substitute primary fuel
- existence of legal requirements on the quality of residues of thermal processes
- treatment of specific input material with high concentration of hazardous substances and low calorific value

3.2.4 Plasma technology

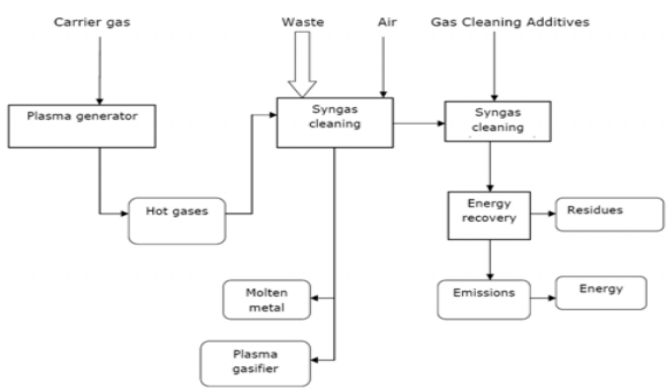
Plasma refers to every gas of which at least a percentage of its atoms or molecules is partially or totally ionized. In a plasma state of matter, the free electrons occur at reasonably high concentrations and the charges of electrons are balanced by positive ions. As a result, plasma is quasi-neutral. It is generated from electric discharges.

Plasma technology can be used as a tool for green chemistry and waste management [12]. Plasma technology is very drastic due to the presence of highly reactive atomic and ionic species and the achievement of higher temperatures in comparison with other thermal methods. In fact, the extremely high temperatures (several thousand degrees in Celsius scale) occur only in the core of the plasma, while the temperature decreases substantially in the marginal zones [13].

Five distinct categories of processes are used as the basis for the plasma systems catering for waste management. These are:

- Plasma pyrolysis [44]
- Plasma combustion (also called plasma incineration or plasma oxidation)
- Plasma vitrification
- Plasma gasification in two different variants [45]
- Plasma polishing using plasma to clean off-gases

A schematic of plasma technology for WtE is shown below



Picture: “Plasma Assisted” gasification [46]

The plasma technology can be used for the thermal treatment of any type of waste. The only variable is the amount of energy that it takes to destroy the waste. Consequently, no sorting of waste is necessary and any type of waste, except nuclear waste, can be processed.

3.2.5 Comparison between thermal treatments of Waste

Summarizing the main characteristics of the common thermal techniques for waste management, the following table presents the basic products and the main operation conditions.

Parameter	Incineration	Pyrolysis	Gasification
Operating Condition			
Temperature ^{0}C	800-1450	250-950	500-1600
Pressure (Bar)	1	1	1-45
Atmosphere	Air	Inert/ Nitrogen	Gasification Factor: O_2, H_2O
Stoichiometric relation	>1	0	<1
Products			
Gas Phase	CO_2, H_2O, O_2, N_2	H_2, CO, H_2O, N_2, H/C	H_2, CO, CO_2, CH_4, H_2O, N_2
Solid Phase	Ash, Scoria	Ash, Scoria	Ash, Scoria
Liquid Phase		Pyrolysis Oils & H_2O	

Table 2. Parameters of typical operation conditions & products of the common thermal management practices [38].

4. Methodology

4.1 Data Collection:

The field work of this study couldn't be conducted due covid 19 pandemic. A detailed survey was conducted In Dhaka city by KM Nazrul Islam [1] 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 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. 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 city (6) and (7) were used to model the energy generation through MSW incineration plant, and (8) were used to model the CH4 emissions from landfill. Equations (10) and (11) were used to model the net carbon emission.

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 1.

4.2 Projected Future MSW Generation.

Future MSW generation was projected for Dhaka 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, and average growth rate in the per capita waste generation was computed from historical waste generation (2001 to 2019) [2]. Projected waste generation was calculated using

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

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:

Compound annual growth rate (CAGR) of population in the respective city was calculated at first using census data [3]. 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 [4]. Waste generation growth factor is calculated as 0.028 (4%× 70%). Projected waste generation was calculated using

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

4.3 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 [5]. Physical characteristics of MSW stream of Dhaka city was 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 [6] .Moisture content (%) and dry weight fraction (%) of MSW were calculated using (3) and (4).Wet weight fraction (%) of MSW of Dhaka city was rounded off to the nearest whole number.

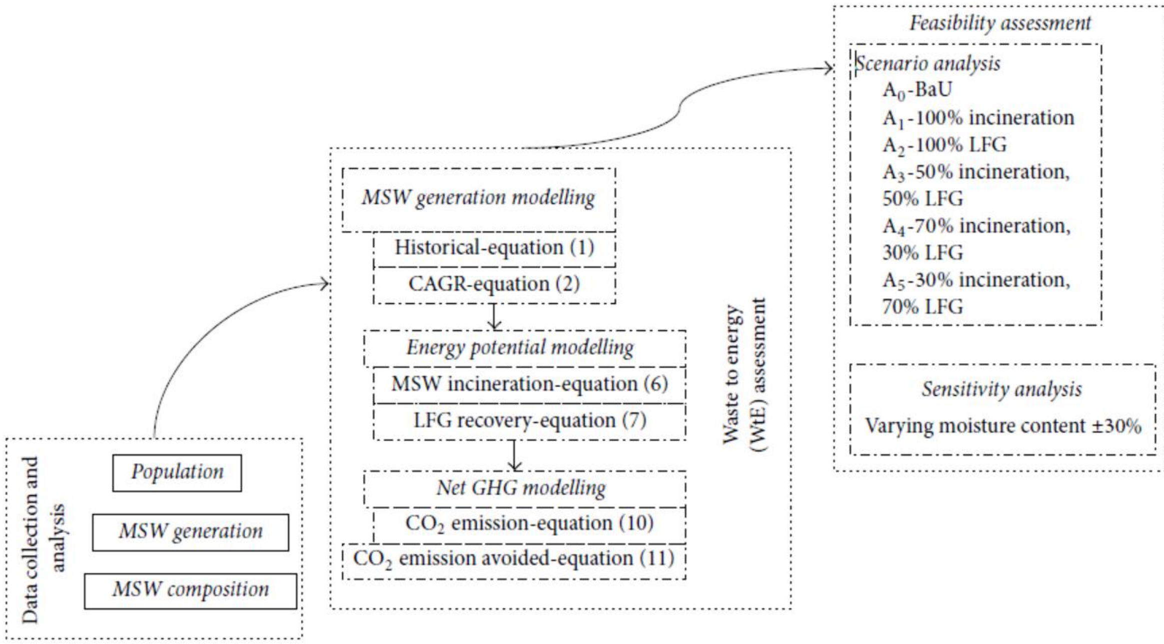


Figure 1: Methodological approach of the study.

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

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.

$$X = Y \times (100 - Z) \qquad (4)$$

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 city are presented in Table 1.

4.4 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 [7]. Under ideal situation MSW combustion processes chemical reaction is represented using (19)

Organic matter + Excess air = CO_2 + H_2O + O_2 + N_2 + Ash + Heat (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 is computed by ultimate analysis and compositional analysis. Under the ultimate analysis, LHV of MSW of Dhaka and was estimated using the mathematical correlation of the modified Dulong equation, as shown in (6) [8]. Under the compositional analysis, LHV of MSW of Dhaka and 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 [9].

Energy content (LHV in kcal/kg) =

$$\{7831X_{Corg} + 35932(X_{H2} - \frac{XO2}{18}) + 2212X_S + 354X_{Ciorg} + 1187X_{O2} + 578X_{N2}\} \times (100 - MC) \quad (6)$$

The values of the variables in (6), such as C_{org}, C_{iorg}, and MC (moisture content), are presented in Table 1.

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

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

4.5 CH4 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 [10]. The global warming potential (GWP) of CH_4 was taken as 34 [11]. Methane emission from SWDS was estimated using (8), and adopted parameters are presented in Table 6.

CH4 emission (tones/year) =

$$(MSW \times MSWF \times MCF \times DOC \times DOCF \times FM \times X - RM)(1 - OF) \quad (8)$$

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 [12]. During the field visit of this study, this was also revealed and presented in Table 1. 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 >5m waste height, MCF = 0.8; and for open dump with <5m waste height, MCF = 0.4 [13]. As reported in Table 1 all the existing open dumping SWDS in Dhaka is of height greater than 5m, so MCF value was taken as 0.8.

(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).

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

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 [14].

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

(e) RM (recovered CH4) and OF (oxidation factor): since no methane recovery takes place in Dhaka in open dumping SWDS, RM is zero and oxidation factor (OF) was also taken as zero as per IPCC default value [15].

4.6 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 [16].Because the combustion of MSW for WtE project though CO2 is emitted, it avoids the use of fossil fuels and the release of CH4 from SWDS. This type of WtE project can also account for carbon credit, because combustion of MSW and associated electricity generation avoid CO2 emission from fossil fuel[16]. In this study, CO2 emissions from WtE project under different scenarios analysis were estimated using CO2 emissions from

$$\text{WtE project } \left(\frac{tCO2}{tMSW}\right) = \sum_j (\text{WFj Ciorgj} \times \text{OFj}) \times \text{Z} \qquad (10)$$

In (10), WFj is dry weight fraction of waste component j; C_{iorgj} is anthropogenic carbon fraction of component j; OFj

is oxidation factor, with the default value of 1 for MSW; Z = C to CO2 conversion factor, with the value of 44/12; and j is component of MSW incinerated.

4.7 GHGs Avoidance:

This study quantified the GHGs avoidance from equivalent CO2 emission avoidance from coal electricity. Bangladesh now is establishing all the coal based power plant to ensure constant supply of electricity in the future [17]. Hence, electricity generated using MSW in Dhaka and city under different scenarios using WtE strategy was assumed to replace electricity generated from coal and so CO2 emission avoidance was computed using

$$\text{CO2 avoidance (tCO2)} = EP_{MSW} \times CF_{EC} \quad (11)$$

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 CO2/KWh was considered in this study [18].

			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
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 1: Physical and chemical properties of MSW of Dhaka

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 2: Typical heat values of MSW components considered in this study[19].

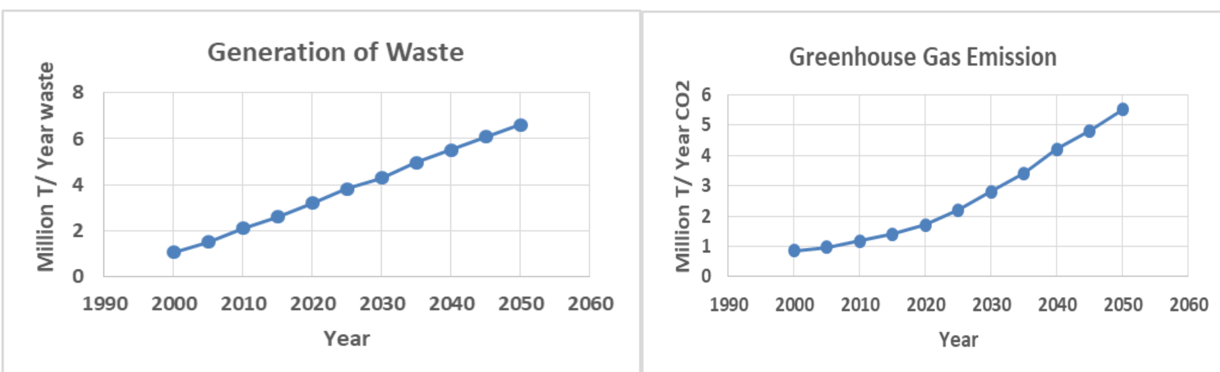
Parameter	Dhaka
MSWF	1
MCF	0.8
DOC	0.158
DOCF	0.77
FM	0.5
RM	0
OF	0

Table 3: Parameters adopted for IPCC default method in this study

5. Result and Discussion

5.1 MSW and GHG Emission Projection:

The actual and projected waste generation and associated GHGs emission in Dhaka from year 2001 to year 2050 are presented in Figure 1.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 approaching in Dhaka city. The associated GHGs emission from untreated MSW also increased gradually from 0.86 million tons CO2 equivalent to 5.5 million tons CO2 equivalent. In Dhaka city, from the generated MSW estimated 1.18 million tons and 1.4 million tons of CO2 equivalent were emitted in 2010 and 2015, respectively and projected to generate 2.8 million tons of CO2 equivalent by 2030 and 5.5 million tons of CO2 equivalent by 2050. It can be inferring that in Dhaka the increasing generation rate of MSW is leading the direct increment of GHGs emission.



(a) (b)

Figure 1: Actual and projected waste generation (a) and associated GHG emission (b) in Dhaka city. Actual wastes generation is from 2001 to 2020 and 2020 onwards represents projection.

5.2 WtE Analysis:

The adopted WtE analysis parameters are presented in Table 1. The LHV of MSW of Dhaka city under the ultimate analysis was 6.32 MJ/KG. Under the compositional analysis, the LHV of MSW of Dhaka city was 0.71 MJ/KG. Ultimate analysis of MSW resulted in a higher LHV value. Heat recovery efficiency of mixed MSW incineration plant is reported as 80 to 90% [21, 23-25]. In this study, heat recovery efficiency of mixed MSW incineration plant in Dhaka city is assumed as 80%. Electricity generation rate of the incineration process using steam turbine was taken as 1MWh/15.65GJ heat [21]. CO2 emissions due to mixed MSW incineration in Dhaka city was 0.046 t CO2/t MSW. Landfill generated CH4 is assumed to have a density of 0.667 kg/m3, LHV of 17MJ/m3 and electricity generation factor of 0.2775 KWh/MJ [21-22]. As mentioned earlier, the energy of MSW in Dhaka can be recovered through mixed MSW incineration plant and LFG recovery.

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 city an estimated 1444 GWh electricity can be produced 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 2132GWh for Dhaka. From WtE analysis, it was observed that MSW incineration has a higher electricity generation potential 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 [26] and LFG recovery [27].

Table 1: WtE analysis parameter adopted for this study

MSW incineration	**Parameter**	**Value**
LHV of MSW	Ultimate analysis	6320 MJ/tMSW
	Compositional analysis	710MJ/tMSW
	Heat recovery efficiency	80%
	Electricity generation rate	1MWh/15.65GJ
	Operating time	24 hours
Landfill	CH4 emissions	0.024 tCH4/tMSW

	Methane GWP 34 - CO_2 emission factor	0.827 tCO_2 equ./tMSW
	CH_4 volume conversion factor	667m3/ton of CH_4
	Calorific value of CH_4	17 MJ/m3
	Electricity generation factor j	0.2775KWh/M
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

5.3 Economic Analysis:

The design capacity of mixed MSW incineration plant to generate electricity in Dhaka 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 is assumed as $36 per ton of MSW per day [28], and operation and maintenance costs as $60 per ton of MSW [29]. 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 city is assumed as $14 per ton of MSW per day, and operation and maintenance costs as $10 per ton of MSW[29]. Carbon credit revenue is assumed as $15.2 per ton of CO_2 [30]. Electricity sales revenue is taken from the residential tariff rate ($0.13/KWh) of Dhaka Electric Supply Company Limited (DESCO), 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 city is comprised. 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 CO2 from coal based power plant. Approximately US $535 million of revenue can be generated from the sales of electricity and claiming of carbon credits from MSW incineration and LFG recovery, in Dhaka 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 of revenue in Dhaka 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.

5.4 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 2). 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 is presented in Figure 2. The net GHGs emission for all scenarios ranged from −0.29 to 0.81 tCO2 equivalent/t MSW. The negative value in net GHGs emission represents the idea that this respective strategy avoided more CO2 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 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.

Table 2: Scenario description for the WtE option in Dhaka, Bangladesh.

Scenario	Description
Scenario A0	Business as usual (BaU) scenario representing no WtE implementation
Scenario A1	All the MSW will be incinerated to generate electricity under the WtE project.
Scenario A2	All the MSW will be landfilled to generate electricity from LFG, under the WtE project.
Scenario A3	50% MSW will be incinerated and 50% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.
Scenario A4	70% MSW will be incinerated and 30% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.
Scenario A5	30% MSW will be incinerated and 70% MSW will be utilized through LFG recovery system for integration of WtE (landfill and incineration) strategy.

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 CO2 than what it generates because of higher avoidance of coal generated electricity. Scenario A1 was the best WtE strategy, generating 0.37 MWh/tMSW of electricity with −0.29 tCO2 equivalent/t MSW of net GHGs emissions. When half of the MSW was incinerated and remaining half for LFG recovery system (scenario A3), a total of 0.27MWh/t MSW of electricity production and a moderate rate of net carbon emission (0.17 tCO2 equivalent/tMSW) were observed. On the other hand, better performance (0.31MWh/tMSW of electricity and −0.01 tCO2 equivalent/tMSW of net GHGs emissions) was also observed in scenario A4 compared to scenarios A2, A3, and A5, where MSW incineration was the key strategy (70% MSW incineration and 30% LFG recovery system) for MSW management in Dhaka city.

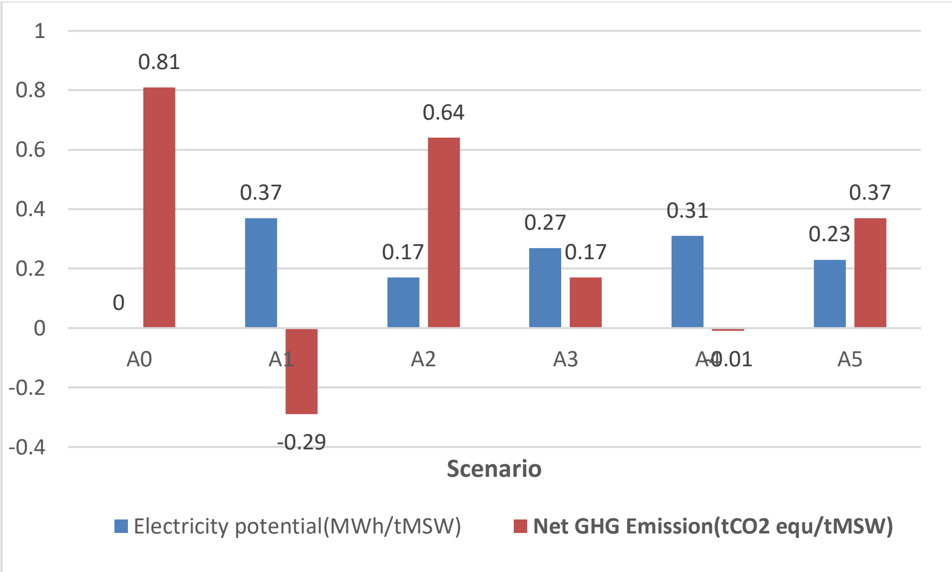


Figure 8: Energy potential and net GHG emissions of different WtE scenarios in Dhaka city, Bangladesh.

5.5 Costs and Profit Analysis:

No energy recovery is currently instigating in Dhaka city under BaU scenario (scenario A0). So operating costs represent the current costs for managing (collection to disposal) the MSW in Dhaka city. In Dhaka, the operating costs for the ongoing MSW management practices are approximately BDT 626.24 ($7.97)/ton of MSW [20] Hence, these costs were considered as operating cost for BaU scenario (scenario A0). Figure 3 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 A1 was the best WtE strategy with the highest profit of US $16.73/ton of MSW. Scenario A1 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 A4, with the second highest profit of US $11.87/ton of MSW.

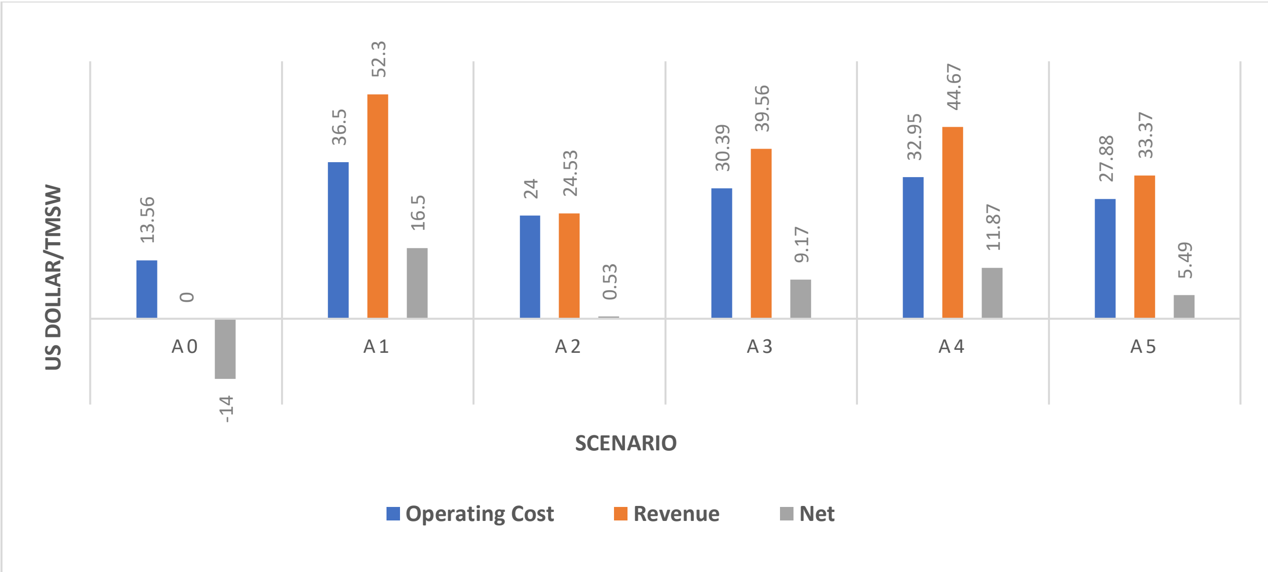


Figure 9: Costs and profit analysis of different WtE scenarios in Dhaka city, Bangladesh.

5.6 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 A1 performance was evaluated, because it was identified as best option for WtE strategy for the management of MSW in Dhaka city, Bangladesh. The results of the sensitivity analysis varying the moisture content of MSW are analyzed. 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 city and also reduce GHGs emissions.

6. Future Opportunities:

Today's energy requirement increasing in trend due to population growth, economic and technological advancement. Also on behalf of new energy exploration condition and present energy consumption rate, whereas discovered energy will deplete within a few decades. Energy has been reported as a critical component in our lives. The primary energy resource situation of Bangladesh is not good at all in comparison with world energy. The proved reserved of oil, natural gas, coal, and hydropower in Bangladesh are limited and larger scale of infrastructure development needed in the country so that we have to find alternative sources of energy. In this perspective SWM will be a good alternative in respective of Bangladesh.

The agitated race of human society towards modern urban life around the world generates tremendous amount of municipal solid waste (MSW), because the generation rate is mounting even faster than the rate of urbanization. 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, 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 approaching in Dhaka city. 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.

7. Conclusion:

Successful solid waste management in a sustainable way can be achieved only through a joint involvement of all stakeholders. Dhaka city has been growing without much of plan and the city lacks systematic waste management system as well.

From the results, a conclusion can be made that the amount of organ waste is still the highest. A comparison of the waste from different sources indicated that it is the same as the results obtained by targeted sampling. The sampling by source did give a good understanding of the waste that is generated by the different sources.

Finally, when evaluating the amount of energy that could be recovered by incineration, it could be said that incineration does give high returns on energy while staying low on environmental effect and on the energy consumed to treat the MSW. 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 city.

WTE strategy for the management of MSW in Dhaka 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. Hence, this technology needs to be developed and understood in order to be implemented for treating the waste generated in Dhaka City.

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Abbreviation

BaU= Business as usual

CAGR= Compound Annual Growth Rate

CO2= Carbondi-Oxide

GHG= Green House Gas

LFG= Land Filled Gas

LHV= Lower Heating Value

MJ= Mega Joule

MSW= Municipal Solid Waste

WtE= Waste to Energy