ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

Techno-economic and Feasibility Analysis of a Thermo-chemical Waste to Energy Conversion Technology from the Perspective of Dhaka City, Bangladesh.

And

Economic and environmental analysis of combined use of biogas generated from landfill and sewage treatment plant.

B.Sc. Engineering (Mechanical) THESIS

BY

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Certificate of Research

The thesis title "**Techno-economic and Feasibility Analysis of a Thermo-chemical Waste to Energy Conversion Technology for Dhaka City, Bangladesh**" and "**Economic and environmental analysis of combined use of biogas generated from landfill and sewage treatment plant**" submitted by **Mohammad Masrur Hossain** (160011083) **and Md. Navid Inan** (160011050) has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering on March 2021.

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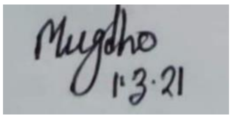
Candidate’s Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidates’



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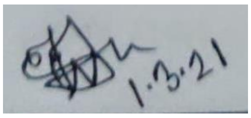

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Part-II

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Abstract

As a consequence of dynamic growth in its economy, Bangladesh has seen rapid urbanization in recent years. Dhaka, the capital of Bangladesh, serves as the economic, cultural, and educational center. Unfortunately, Dhaka has severe issues with its urban planning, and its unreliable waste management system results in waste accumulation in different neighborhoods. The generation of MSW is growing fast in Dhaka city as it is directly related with economic development and urbanization. Hence, the necessity of a comprehensive waste management system and the use of appropriate Waste to Energy Technologies (WTE) is a crying need in the present scenario of Dhaka city. Electricity generation concept comes as an alternative energy source. This concept of electricity generation utilizing municipal solid waste is highly encouraged in the national waste management policies of Bangladesh. But due to the lack of proper attention, this concept is still underdeveloped and requires more improvement. Under this consideration, the purpose of this study is to evaluate the energy generation potential, the economic viability, and the environmental impact of a municipal solid waste-based incineration WTE conversion power plant in Dhaka city. In the second study, we have analyzed the energy generation potential of biogas collected from landfills and sewage treatment plants in Dhaka city. Energy potential for six scenarios was analyzed along with economic analysis. To do so, waste collection prediction was conducted. IPCC model was used to calculate the biogas generated from landfills and Von Sperling's method to quantify biogas production from the sewage treatment plant. The best scenario was the combined use of biogas from both plants to produce electricity with a generation capacity of 21 MW and a payback period of 10.70 years.

Nomenclatures

HHV_d	Higher heating value at constant volume	ET	Emission by vehicle (ton/y)
HHV_P	Higher heating value at constant pressure	ER_d	Emission of harmful gases by fuel (tons)
I_0	The amount of total capital expenditure at year zero	Em	Emission factor of fuel (ton/MWh)
$OMEX_t$	At year t, the aggregate of fixed and variable operation and maintenance expenditure	PE	Percentage of energy shared by a fuel
L_t	Expenditure associated with landfilling the generated residue WTE conversion power plant.	W_t	Amount of treated waste to be used as the feedstock of WTE power plant at year t (ton)
E_t	Aggregated electricity generation at year t (MWh)	M_f	Annual biomass requirement
n	Economic life of the WTE conversion power plant	E	Annual energy generated (MWh)
r	Weighted average cost of capital	η_0	Efficiency of the plant
D	Hauling distance (km)	EF_t	Emission factor of vehicle (ton/km)
TT_l	Weighted average truckload per trip (ton/km)	E_e	Reduction of emission by displaced electricity from grid
E_b	GHG emission intensity		

Greek Symbols

η	Efficiency

Acronyms

MSW	Municipal Solid Waste	BPDB	Bangladesh Power Development Board
WTE	Waste-to-Energy	BFB	Bubbling Fluidized Bed
DNCC	Dhaka North City Corporation	CAPEX	Capital expenditure
DSCC	Dhaka South City Corporation	OMEX	Operation and maintenance expenditure

IRENA	International Renewable Energy Agency	WACC	The weighted average cost of capital
LHV	Lower Heating Value	MC	Moisture Content
HHV	Higher Heating Value	IRR	Internal Rate of Return
NPV	Net Present Value	MIRR	Modified Internal Rate of Return
LCOE	Levelized Cost of Energy	LCOW	Levelized Cost of Waste
PI	Profitability Index	PP	Payback Period

Chapter 1: Introduction

1.1 Current Scenario of Waste Generation Worldwide

The International Energy Agency (IEA) in 2013 estimated that around 1.3 billion tons of waste was generated worldwide; they also predicted that this amount of waste generation would reach 2.7 billion tons by 2050 [9]. By the end of the 21st century, it is estimated that the global population will rise to 11 billion people. A higher population growth rate is seen among the lower-middle income population, and most of the lower-middle income population is centered in Asia, the Middle East, and Africa. Around 90% of growth will take place in Africa and Asia [10][11]. This uncontrolled population growth is positively correlated with unplanned urbanization. The world bank in its report "What a waste (2012)" referred to the increasing urbanization as the major cause of increasing Municipal Solid Waste (MSW) generation, as it is seen that the urban population produces up to twice as much as waste than the rural population [12]. Per capita MSW generation has seen a steep increase from 0.64 kg/capita/day in 2002 to 1.2 kg/capita/day in 2012 and the value is predicted to reach 1.24 kg/capita/day by the end of 2025 [12]. Due to this drastic MSW growth, it is of prime importance to establish a resilient waste management system.

1.2 Problems with Landfill and Household Sludge

Landfilling is a common practice of disposing of waste from an early era. Considering the technological and economical aspects, recycling all wastes is not feasible and landfilling becomes a suitable option all around the world. It is a technique of compressing the wastes with inert materials or clay layer by layer. With the increase of population and urbanization and industrialization, two types of wastes are continuously generated: municipal solid waste and household effluents. The generation of waste is specially higher in urban areas of developing countries like Bangladesh [13]. Thus handling and disposal of wastes is becoming difficult leading to health and environmental problems [14]. Most of the wastes are disposed of in landfill sites which are mostly near residential areas. Emission of Landfill Gas (LFG) occurs from the residues of wastes in landfill sites through chemical and biological processes. LFG mainly comprises of CH4 (50-60%) and CO_2 (40-50%) [15] as well as compounds of nitrogen and other volatile compounds. Methane and CO_2 are the primary greenhouse gases responsible for global warming. One ton of methane has a greenhouse effect of 72 times more than carbon dioxide over a period of 20 years [16]. Intergovernmental Panel on Climate Change reported that 30% of the total methane emitted to the atmosphere is by landfill [17]. Researchers estimated that about 30-70 million tons of methane gas are transmitted from landfills per year [18]. Several studies reported that adverse environmental impact caused by landfilling is much higher than other waste management systems [19]–[21]. Without recovering the emission gas, landfilling has a global warming potential of 746 $kgCO_{2eq}$/MWh of energy generation [22]. Thus quantification of emission of methane gas from landfills is a significant factor to evaluate measures for reducing greenhouse gas. Quantification of methane emission from landfill protocols has been adopted by the United Nations and the European Union. Again leachate generated from landfilling is harmful to soil, groundwater, surface water. Therefore, proper handling and mitigation of landfill gases bring important health and climate benefits.

Power generation from methane is a useful way of mitigating emission gas. At present fossil fuels are the primary source of power which meets almost 84% of energy demand globally [23]. With the increasing population and industrialization, it is predicted that global energy demand will be six times more than the current need [24]. Waste to energy technology like the usage of landfill gas is considered a potential source of power. Bove and Lunghi reported that one ton of MSW can release 120-300 m3 of emission gas which has a potential to generate 5.9 KW per hour per cubic meter [25]. Municipal sludge contains chemicals from industries, soaps, bleaching [26] and heavy metals like chromium, arsenic [27]. Sludge dumped in the environment comes in contact with rain and flood and contaminates surrounding inhabitants. Instead of releasing into the environment using this biogas for power generation can provide significant energy, economic and environmental benefits. It can reduce emission of greenhouse gases at the same time decrease burden on non-renewable resources.

1.3 The City Under Study

Dhaka was chosen for this study. Dhaka is located in the central part of Bangladesh at a latitude of 23º22' North and a longitude of 90º22' East on the banks of the river Buriganga. With a total surface area of 306 square km and divided into two municipalities: Dhaka North City Corporation (DNCC) and Dhaka South City Corporation (DSCC).

1.4 Dhaka City's Perspective

In Bangladesh, massive growth in socio-economic activities is seen around the big cities in recent years. This leads to the exponential growth of population, unplanned urbanization, and industrialization leading to the production of a vast volume of garbage. This situation is not so much different in the rural area of Bangladesh. In Asia, 1 million tons per day waste is generated, which is expected to rise to 1.8 million tons per day by 2025 [28]. In Bangladesh, the total waste generation will reach 47000 tons/day by 2025 [29].

Different parameters affect waste generation; among them lifestyle, socio-economic status, and literacy rate have a significant impact. As a result of economic development, people in Bangladesh are adapting to the lifestyle of the developed country, leading to the generation of a large quantity of waste. Dhaka, the capital of Bangladesh, is the center of major social-economic and political activities and home to around 20 million people. Due to the unsanitary MSW management system of Dhaka, the environment gets affected directly or indirectly. Besides, unsanitary MSW management can cause serious health risks for the inhabitants of the municipal, which is validated by the Dengue and Malaria outbreak seen in recent years. The UN climate summit held in 2014 reported that MSW dumpsites and landfills are one of the largest anthropogenic sources of CH_4 emission. CH_4 is 28 times more potent global warming substance compared with CO_2 [30]. In addition to CH4, around 800 tons of CO_2 is emitted into the atmosphere [31]. Reduction in GHG is possible by capturing the deposited waste's energy potential [32]. Besides the GHG emission, leachate generated from MSW pollutes surface water, groundwater, and soil. But if proper measures are taken, this MSW can be used as an energy source to fulfill our ever-growing energy demand.

As Bangladesh has seen enormous growth in the economy in recent years mostly centering the capital, Dhaka city. This has led to a large shift of village workforce to Dhaka and unplanned urbanization. Dhaka which is home to about 20 million people with the continuous growth of population and unplanned urbanization and industrialization is facing a massive increase of the volume of waste. They are mainly dumped at different landfill sites without proper handling. Matuail landfill site received about 2000 tons of household, industrial and commercial waste alone in the year 2016 [33]. Lack of proper management of landfill sites and usage of emission gas causing serious health issues like outbreak of dengue, malaria among the local people as well as emission of greenhouse gases. On the other hand, untreated household sludge and industrial effluents are polluting four rivers around the capital at 577 spots [34]. Buriganga river alone is polluted by 95,000 L of untreated tannery waste per day [35]. Govt. is facing challenges with such a huge amount of untreated landfill and sewage wastes. Before taking any project to generate power from wastes it is necessary to quantify the biogas gas generation. Several studies have been performed related to landfill management in Bangladesh such as landfill area estimation [33][36], recycling aspects [37], greenhouse gas generation [38], treatment strategies for landfill leachate [39]. Several types of research were conducted to demonstrate the use of sludge in making construction materials in Bangladesh. Ariful Islam has studied properties of tannery sludge-incorporated clay bricks [40]. Another author suggested that use of textile waste to make fired clay bricks can be a possible replacement of dumping it in environment [26]. But comprehensive research on power generation from biogas for the case of BD is still lacking.

1.5 Background of This Study

The MSW management system is segmented into different components: the first component of the MSW management involves the physical components of the system, which includes the whole chain starting from generation of waste to collection treatment disposal of waste; the second component involves analyzing the governance aspects, which includes the role of stakeholders, the financing system, legislation as well as socio-cultural aspects. This complex chain of the relation between different segments is required to serve appropriately in order to create a resilient waste management system. Initially, the prime purpose of waste management was to develop a proper waste collection system by maintaining higher standers of public hygiene. However, over the years, the concept of waste management got evolved: this evolved concept additionally includes the concepts of waste recycling, energy generation by using WTE technology, and environmental protection [41].

Electrical energy is the primary input and one of the basic needs of socio-economic development and urbanization. With the increase in population, the energy consumption rate is growing in Bangladesh. Coal, natural gas, petroleum is the primary source of energy. Nuclear fuel-based power plant will be operational in the near future to fulfill this increasing energy demand. Using fossil and nuclear fuel-based power, we are filling our energy demand to the most extent, but we are still lagging. Besides, conventional power plants are causing severe environmental pollution. At present, fossil fuels are considered the most reliable energy source for their low production cost and meet approximately 84% of global energy demand [23]. But several studies concluded that WTE technologies are both sustainable and economically feasible for developing countries like Bangladesh [42].

The International Renewable Energy Agency (IRENA) projected that roughly 13 GW of power could be produced globally by using WTE technology [43]. In different studies conducted on Southeast Asian countries such as Bangladesh, India, Sri Lanka suggested that WTE technology presents a unique opportunity under the present circumstance [14, 15, 16]. But the advanced concept of solid waste management such as "Zero Landfilling," which is adopted by the developed Asian countries such as South Korea Japan, is certainly expensive for the underdeveloped countries [47].

Biodegradable and non-biodegradable is the primary classification of MSW. On the other hand, Biochemical and thermochemical are the main classification of WTE technologies. Biogas is produced with the help of anaerobic digestion related to the biochemical process and pyrolysis; gasification and incineration are the WTE technology that involves the thermochemical process [48]. The choice of suitable WTE technology depends on the type of waste used as the feedstock, environmental impacts, capital investment and revenue-generating potential. Among the different WTE technologies considering different parameters like land scarcity, carbon footprint, thermal treatment is a suitable WTE conversion method, and incineration is widely used around the world. Incineration is a process of controlled burning of MSW at a temperature greater than 800^{o} Celsius by destroying the residues. This WTE process also involves heat generation, which can be utilized to generate electrical power. In addition to generating energy, it also reduces the waste volume, so there is less stress on landfills. So indirectly, thermal treatment increases the lifespan of the landfill. However, landfills are still required to safely store the waste by-product from the thermal treatment of MSW. There are around 600 incineration plants in operation in different countries worldwide, which are incinerating around 181 million tons of MSW for generating electrical power [49]. Different studies on GHG emission from the incineration plant indicated that energy recovery through incineration can mitigate GHG emissions [50]. Incineration is a traditional and well-established process that has improved over the years [32]. The incineration process causes the emission of dioxins and the production of residue containing a higher number of solid particles and metals. So, while considering the WTE process involving incineration, environmental control is essential and this process requires continuous monitoring of emission, leading toward the requirement of higher capital costs and operation and management costs. Studies show that a well-controlled incineration plant has less environmental impact than landfilling of waste with or without LFG extraction [51]. Besides, the distributed power generation system, which is not connected to the national grid, can be created by using the incineration plants [52].

1.6 Objectives of This study

In the context of the presented scenario above and with the intention to propose a better MSW management system with an adequate energy extraction scheme, this study is conducted to determine and assess the viability of the investment in the field of WTE in the context of Dhaka city by evaluating the environmental and economic impact of MSW based incineration power plant. The applied methodology in this paper and the obtained results can be utilized in the context of other cities located in the similar environmental condition of Bangladesh and can be used as a subsidiary tool for developing waste management planning.

This study also aims to predict the amount of biogas generation from landfill and sewage treatment plant and their electricity generation potential. This will allow addressing waste as a power generation resource rather than a burden to be disposed of. Although it is difficult to measure methane emissions from landfills, it can be an excellent opportunity for recycling harmful methane gas [53]. For proper calculation of the potential of LFG quantitative data of total wastes, their composition and LHV value are required. Researchers have introduced several models to predict the amount of LFG generation such as IPCC-model, LandGEM, TNO-model, simple Afvalzorg, multiphase Afvalzorg, EPER Germany models. In this paper IPCC(2006) model was used to determine the energy potential from landfills [54]. For sewage treatment plant model developed by Von Sperling was used [55]. Several scenarios were considered including the combined use of biogas from both plants with an aim to compare different possibilities of energy production. Financial analysis was also done based on NPV, LOCE values. Results obtained by using different models were compared and presented in graphical form and reasons behind the variations were predicted. Most of the data in this paper are related to Dhaka and were collected from literatures and relevant authorities.

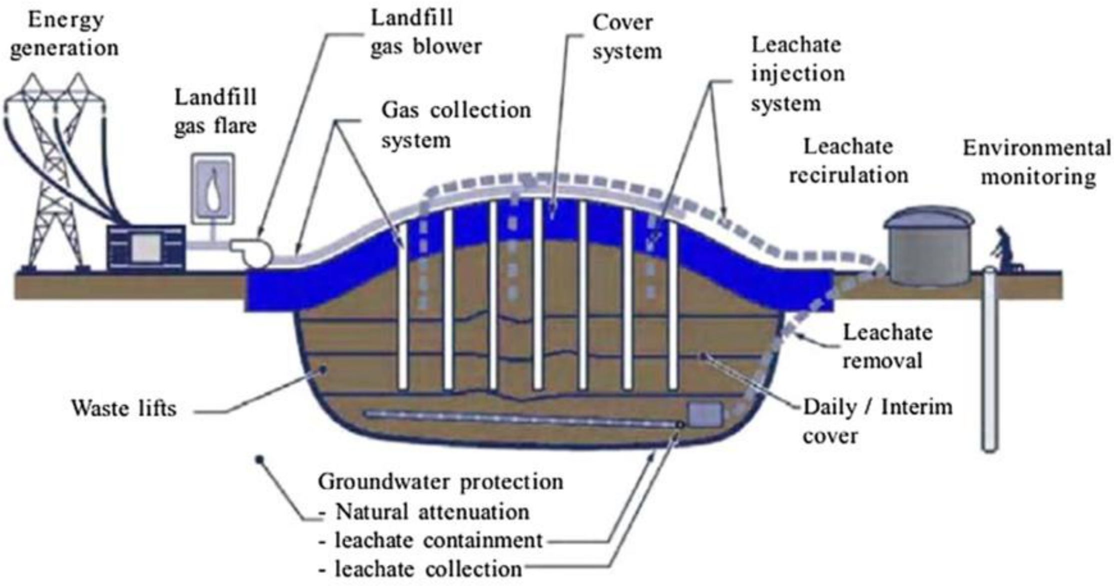

Fig. 1.1: A typical engineered landfill with a biogas recovery system. [7]

Chapter 2: Waste to Energy Options

2.1 Major WTE Technologies

There are three major waste to energy technologies which are widely used where waste is used as fuel to produce power. Such as- Gasification, Anerobic Digestion and Incineration. Gasification is a thermal conversion technology where organic compound gets converted to syngas in controlled atmosphere of oxygen. This syngas is burnt in presence of oxygen at a very high temperature to produce energy. Anaerobic digestion is the microbial degradation of organic biodegradable matter in absence of oxygen producing biogas. Biogas can be used as fuel. Incineration was initially used for volume reduction. But with the advancement in air pollution control technologies, it is currently considered as an attractive waste treatment option. In this system complete oxidation of feedstock is done at 800^0 C.

2.2 Incineration Technology

For this work incineration technology was used for several reasons which are described below:

1. All types of wastes can be used: In the figure of average recoverable energy vs different wastes ([56]) we can see that gasification is the best technology when only plastic is used as fuel. For food waste and yard waste anaerobic digestion is the most optimum technology. But we cannot use food waste and yard waste in gasification. Again, we can't use plastic, textile waste in anaerobic digestion plant. But all types of waste can be used in incineration plant. As all types of wastes can be used, we have a scope of using any type of waste we want, also the unsorted raw MSW. Recyclable wastes can be used for other purposes.

2. Waste mass and volume can be reduced by 80% and 90% respectively: Reduction of volume is helpful for small cities like Dhaka as the landfill area requirement will be less.

3. Harmless end products: One of the characteristics of MSW incineration is the complete destruction of any living organisms and mineralization of organic substances into harmless end products. For purification of exhaust gas, advanced pollution control systems are used such as-

- Lime powder is sprayed to neutralize and remove the polluted acidic gases (sulfur oxides, hydrogen chloride).
- Activated Carbon is injected to adsorb and remove any heavy metal and organic pollutants (e.g., dioxins) in the exhaust gas.
- Bag house filter - to filter and remove dust and fine particulates.

4. As it is a cleaner source of energy, so the plant can be constructed near residential area.

5. Bottom fly ash can be utilized in road construction and cement production.

2.3 Methane Generation Stages

Landfill gas (LFG) mainly comprises of methane (CH_4) and carbon dioxide (CO_2). It contains small quantity of sulfides, oxygen, nitrogen, hydrogen, carbon monoxide, ammonia and non-methane organic compounds (NMOCs). Municipal Solid Waste (MSW) deposited in landfills convert to LFG through a number of processes and phases. LFG is produced mainly by three processes such as bacterial decomposition, volatilization and chemical reactions. A small fraction of LFG is produced when certain wastes primarily organic compounds change into vapor from a solid or liquid phase.

NMOCs are created when certain chemicals like chlorine bleach, ammonia react with each other. Methane, a major greenhouse gas, is produced through the bacterial decomposition of biodegradable fractions of waste. The process occurs in four stages: [8]

Phase 1: During this phase, aerobic bacteria present in waste and soil that can survive only in oxygen absorb the oxygen. At the same time they break down the large molecular chains of compound carbohydrates, lipids and proteins present in the organic waste into soluble molecules. Major byproducts of this phase are carbon dioxide, water and heat. Depending on the amount of oxygen present this phase can last for days or months. Oxygen level varies based on how compressed or loose the landfill waste was when it was buried.

Phase 2: When all the oxygen in the landfill is used up, anaerobic decomposition starts. Acid-forming bacteria convert the molecules produced in phase 1 to simple organic acids, alcohols, carbon dioxide and hydrogen. Thus the landfill area is converted to acidic in nature. The acids produced are acetic, lactic and formic acids and the alcohols are methanol and ethanol. The duration of this phase is one to six months.

$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

Phase 3: Organic acids produced in phase 2 are consumed by certain types of anaerobic bacteria in phase 3. The product is acetate. This process makes the landfill environment neutral for methane producing bacteria to grow. There is a symbiotic relationship between acid and methane producing bacteria. Compounds produced by acid-producing bacteria are consumed by methanogenic bacteria. Acetate and carbon dioxide are consumed by methanogenic bacteria, excess of which is toxic for acid-producing bacteria.

Phase 4: The production rate of landfill gas remains constant as well as the composition at this phase. The LFG contains approximately 50-60% of methane, 40-50% of carbon dioxide and 2-9% of other gases by volume. Methane is produced either by a breakdown of acetate or by the reduction of carbon dioxide by hydrogen [57]. The production rate remains stable for about 20 years. However gas will continue to generate for about 50 or more years after the waste is dumped in the landfill [58]. If more organic wastes are present, gas production may last longer.

$CH_3COOH \rightarrow CH_4 + CO$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

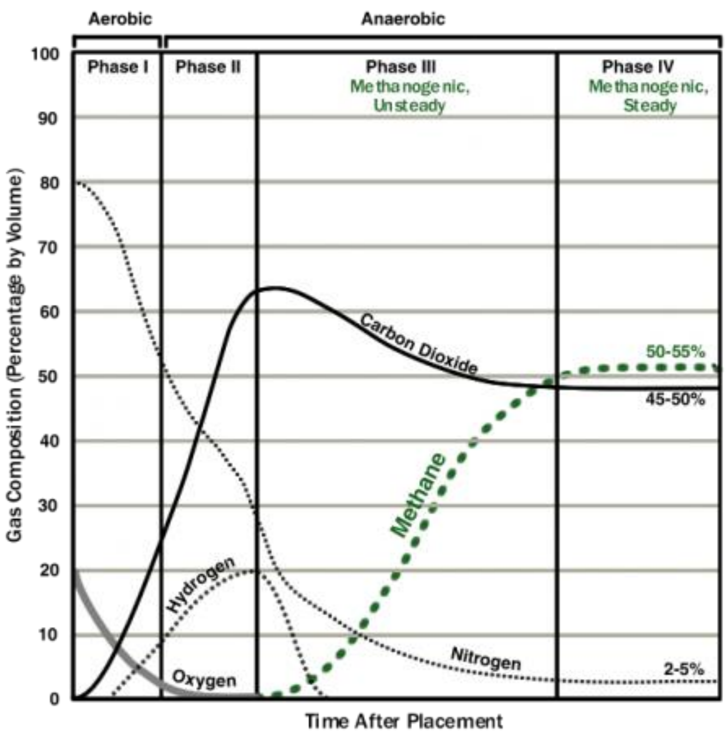

Fig. 2.1: Production phases of LFG (ATSDR, 2001) [8]

Landfill gas production rate and volume alter depending on the conditions of the waste and few environmental factors. Methane and carbon dioxide production will increase if more organic waste is present in the landfill. LFG generation is higher in the first 10 years of dumping and it is maximum during 5 to 7 years after dumping. Increased moisture content and temperature in the landfill increases bacterial activity, thus increasing LFG production. Oxygen content delays the end of first phase, so the landfill site should be highly compacted [8].

Chapter 3: Methodology

Part-I

3.1 Introduction

The data used in this literature is secondary data, collected by extensive reviewing of the local and international reports and research articles published by academic institutions, government, independent agencies, and reputed experts. A financial report titled "Renewable Power Generation Cost (2019)" has been published by IRENA. In this report, IRENA has presented a set of globally acceptable financial models to establish different WTE technologies. These financial models are developed by deriving financial data from existing WTE plants worldwide [59]. According to IRENA (2012), the cost of implementing WTE technology depends on the type of waste used as feedstock. Furthermore, it also depends on the local consumption pattern [60]. To determine the input parameters of the financial model, globally accepted best practices to establish WTE technologies were evaluated. Finally, it enabled us to analyze the impact of the input parameters on the financial model, which is named as sensitivity analysis. The main steps followed were the ultimate and proximate analysis of MSW generated in Dhaka city, financial model development, and sensitivity analysis.

3.2 Physical and chemical composition of MSW

The waste generated on DNCC and the DSCC is categorized as Domestic waste, Industrial waste, and street waste [1], [61]. The mass fraction of the domestic waste in MSW is 48.5%, industrial waste is 31.77% and street waste is 19.71% [61]. As these three different categories of waste have different physical and chemical composition, so LHV is varied among these three different categories of waste. The physical composition of the generated MSW is shown in Table 3.1. The chemical composition of the various physical compositions of the generated MSW is shown in Table 3.2. This secondary data has been collected from different sources to implement in this research. The physical compositions along with the LHV value of the generated MSW are varied from dry season to the wet season. For the calculation, the average LHV is considered. Glass, ceramic, and metals present in the MSW is discarded during the analysis as the mass fraction of these compositions is very low; also, the presence of organic and inorganic carbon is very negligible, resulting in lower LHV for this portion of the waste [2]. As the metals ceramics and glass is recycled for different purposes, the profitability will be higher if glass, ceramics, and metals could be recycled rather than burning or landfilling. As the sand and dust's chemical composition is varied based on the location, standard Calorific value is considered for Sand and Dust, which is 6.44 MJ/kg [62].

Table 3.1

The physical composition of the generated MSW in Dhaka city [1].

Source of waste	Season	Paper	Food Waste	Wood & Grass	Plastics	Textiles and others	Sand and Dust
Domestic waste	Dry season	7%	66%	7%	2%	11%	6%
	Wet season	10%	68%	7%	6%	1%	7%
Business waste	Dry season	16.69%	43.86%	21.27%	1.53%	7.54%	9.11%
	Wet season	14.41%	50.68%	13.41%	5.03%	5.63%	10.84%
Street waste	Dry season	2%	4%	10%	0%	11%	73%
	Wet season	1%	11%	16%	1%	10%	60%

Table 3.2

The Chemical composition of the generated MSW in Dhaka city [2].

	Paper	Food Waste	Wood & Grass	Plastics	Textiles and others
Moisture content	3.2	72.34	38.21	0.53	8.67
Organic carbon (C_{org}, %)	43.50	48.00	47.8	0	55.00
Inorganic carbon (C_{iorg}, %)	0	0	0	60.00	0
Ash (%)	6.00	5.00	4.50	10.0	2.50
Sulphur (S, %)	0.30	2.60	3.40	0.00	4.1
Nitrogen (N, %)	0.20	0.40	0.30	0.10	0.10
Oxygen (O, %)	44.00	37.60	38.00	7.20	31.20
Hydrogen (H, %)	3.00	6.40	6.00	22.80	6.60

3.3 Model development

Incineration is among the most preferable WTE conversion technologies. Utilizing this technology, waste mass and volume can be reduced by 70% and 90%, respectively [63]–[66]. Moreover, the complete destruction of any living organisms and the mineralization of organic substances into harmless end products can be achieved [41]. In Fig. 1, a simple model of a biomass-based power generation system utilizing MSW is illustrated. This process involves raw unprocessed MSW as the fuel of the biomass-based power generation system and electricity as the output ready to be consumed by the end-users.

The process involves direct combustion of MSW in the combustion chamber at an adequate temperature, which produces superheated steam from water that will be used to turn a steam turbine connected to a generator. The generator will produce electricity, which would be transmitted to the national grid using the transmission system.

3.3.1 Equipment used for the power generation system

The power generation system uses a Bubbling Fluidized Bed (BFB) gasifier for the gasification of MSW. The primary advantage of the BFB gasifier is that it allows a diverse range of raw wastes of different particle sizes [3]. The other components of the power generation system include a feedstock handling plant, water treatment plant, condenser, cooling tower, and electrical system for transmission and control of generated electricity.

3.3.2 Incineration WTE conversion facility generation capacity

A 10 MW capacity incineration WTE conversion power plant was considered as suggested in literature [5].

3.3.3 The capacity factor of the WTE conversion power plant

The ratio of processed waste per year to the maximum capacity of waste processing per year is termed as the capacity factor. In this research, we have assumed a capacity factor of 85%, as suggested in the literature [60].

3.4 Assumptions for economic analysis

3.4.1 Ownership, fuel cost, transportation cost and availability of waste as fuel

This research assumes that this WTE conversion power plant will be owned by the state and operated by the Bangladesh Power Development Board (BPDB). So, the buying cost of waste as the feedstock for this WTE conversion power plant is zero and it will be available continuously. The only cost associated with fuel is the fuel transportation cost, which is a variable cost depending upon the capacity factor of the plant. From the available financial report published by DNCC and DSCC, it is found that the weighted average cost of waste transportation in Dhaka city is 5.63 USD/ton [67] (Assuming 1 BDT = 0.012 USD [68]).

3.4.2 Economic life cycle and construction phase

According to the IRENA (2012), the economic life cycle of a biomass-based power plant ranges between 20 to 25 years with a construction period of a minimum of 3 years [60]. So, in this research, we have assumed that the economic life cycle of this plant will be 22 years with a construction period of 3 years.

3.4.3 Capital Expenditure (CAPEX)

The capital cost of setting a biomass-based WTE conversion power plant includes planning, engineering and construction cost, mechanical handling cost and source separation cost of the MSW. According to the IRENA (2012), the capital expenditure cost for WTE conversion power plant utilizing BFB gasifier ranges between 2170 USD/kW to 4500 USD/kW [3]. But according to recent studies, the average capital cost for the WTE conversion power plant utilizing the BFB gasifier is 3925 USD/kW [12]. According to IRENA (2012), the breakdown of capital expenditure is shown in Table 3.3 [3].

3.4.4 Operation and Maintenance Expenditure (OMEX)

The operation and maintenance expenditure can be classified as fixed OMEX and variable OMEX.

Table 3.3

Breakdown of the capital expenditure of the plant [3].

Category	Contribution to Capital Expenditure (%)
Bubbling fluidized bed gasifier system	60
Civil cost	19
Mechanical handling system	4
Consultancy	5
Prime mover	9
Plant electricity	3

3.4.4.1 Fixed OMEX

Fixed OMEX includes the labor cost, insurance cost, scheduled parts maintenance and replacement cost. Fixed OMEX is expressed as a percentage of CAPEX. According to IRENA, the fixed OMEX ranges between 3% to 6% of CAPEX [3]. In this research, we have assumed OMEX to 4% of CAPEX.

3.4.4.2 Variable OMEX

Variable OMEX includes unexpected parts maintenance and replacement cost, fuel cost, fuel and residue transportation cost, residue disposal cost. Variable OMEX is positively correlated with the output of the power-plant. And expressed as a per-unit value of the power plant. According to IRENA for the BFB gasification technology, variable OMEX is 4 USD/MWh power output [3].

3.4.5 Residues of biomass fuel landfilling cost

Using incineration technology, the mass and volume of biomass fuel can be reduced by 70-80% and 80-90%, respectively [29, 30, 31, 32]. In this research, we have assumed an 80% mass reduction of biomass fuel. The remaining 20% of biomass will be landfilled as residue. The waste handling capacity of the landfill is 80% [69] and the cost of landfilling is 5.2 USD/ton residue [12].

3.4.6 Electricity selling price

In this research, the selling price of the generated electricity is assumed according to the retail power tariff. For governmental power generation institutes in Bangladesh which is 0.085 USD/KWh [70] (Assuming 1 BDT = 0.012 USD [68]).

3.4.7 Annual Inflation rate

In this research, it is assumed that the yearly inflation rate of OMEX (both variable and fixed OMEX) is 8% and the annual increment in electricity selling price is 6%. This assumed inflation rate is proposed in recent studies [12].

3.4.8 Depreciation method

In this research, straight-line depreciation is assumed with a salvage value of zero. So, the depreciated amount will be the same each year over the life cycle of the WTE conversion power plant.

3.4.9 Weighted average Cost of Capital (WACC)

In this research, 10% WACC is assumed.

3.5 Mathematical formulation

3.5.1 Determination of heating value

The amount of energy released when the by-products of burning fuel in the presence of oxygen under standard temperature and pressure are entirely brought back to the initial temperature is termed as the Higher heating value (HHV) of that fuel. A lower heating value (LHV) is determined by subtracting the water vaporization heat from HHV. In other words, LHV is the adjusted HHV at the boiler operating condition. The feedstock used in the WTE conversion power plant is the MSW collected from Dhaka city.

HHV of this feedstock at a constant volume (HHV_d) and HHV at constant pressure (HHV_P) are calculated from the composition of each type of fuel using Eqs. (1) and (2) [71]. LHV at constant pressure can be found by eliminating the moisture content (MC) of the feedstock using Eq. (3).

$$HHV_d = 0.3491X_c + 1.1783X_H + 0.1005X_S - 0.1034X_O - 0.015X_N - 0.0211X_{ash} \tag{1}$$

where X_C, X_S, X_H, X_O, X_N *and* X_{ash} indicate the percentage of mass of carbon, sulfur, hydrogen, oxygen, nitrogen and ash in the feedstock, respectively.

$$HHV_p = HHV_d - 0.212X_H - 0.0008\,(X_O + X_N) \tag{2}$$

$$LHV = HHV_p\,(1 - MC) - 2.44 \times MC \tag{3}$$

To find the heating value for all combined wastes the heating value of each type of waste is multiplied by their respective percentage.

3.5.2 Annual feedstock requirement for the WTE conversion power plant

Annual feedstock necessity is determined on the basis of energy demand, the heating value of fuel, system efficiency, and moisture content. Fuel requirement increases with the increase of MC and decreases with increasing efficiency. Eq. (4) is used for estimating annual biomass requirement (M_f) as mentioned in the literature [72]. Results are shown in tons of fuel.

$$M_f = \frac{E \times 3.6}{LHV \times \eta_0} \tag{4}$$

3.5.3 The mathematical formulation for Financial Model

As mentioned above, the financial feasibility of this WTE conversion power plant in Dhaka city is investigated using a set of economic indicators, i.e., NPV, Payback Period, IRR, MIRR, PI, LCOW and LCOE.

3.5.3.1 Net present value (NPV)

For comparison, we would like to bring every cost of consecutive years to year zero, which is done by calculating the net present value (NPV). Net present value (NPV) is the discounted difference between the present values of income and all expenditures for a given period. Eq. (5) is the formula used for calculating NPV [12].

$$NPV = I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + L_t)}{(1+r)^t} \tag{5}$$

3.5.3.2 IRR and MIRR

IRR indicates the value of r at which NPV becomes zero. IRR is calculated using the trial-and-error method. The Modified Internal Rate of Return is determined using the following formula in Eq. (6) [12].

$$MIRR = \sqrt[n]{\frac{Future\ values\ of\ positive\ cash\ flow}{Present\ values\ of\ outlays}} - 1 \tag{6}$$

3.5.3.3 Profitability Index (PI)

It indicates the ratio of the present value of future cash flow and capital expenditure Eq. (7).

$$PI = \frac{Present\ value\ of\ future\ cash\ flow}{Capital\ expenditure} = \frac{NPV}{Capital\ expenditure} + 1 \tag{7}$$

3.5.3.4 Payback Period

The payback period is the estimated time required for the estimated revenues and other economic benefits to recover the initial investment after subtracting operation and maintenance costs. The payback period is calculated to evaluate two or more alternatives. The payback period can be calculated using the following Eq. (8) from the literature [41, 42].

$$PP = \frac{total\ investment}{earnings\ after\ interest\ and\ tax} \tag{8}$$

3.5.3.5. Levelized Cost of Electricity (LCOE) and Levelized Cost of Waste (LCOW)

LCOE is the most widely used methodology to determine the cost of per unit electricity generation from a source. Similarly, LCOW indicates the cost of per unit waste. Both LCOE and LCOW were calculated using the following equations from the literature [12].

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + L_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)t}} \quad (9)$$

$$LCOW = \frac{I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + L_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{W_t}{(1+r)t}} \quad (10)$$

3.5.4 Emission reduction Utilizing this technology

The emission of greenhouse gas (GHG) is a major concern worldwide and in Bangladesh. About 74.5 tons of CO_2 were released in 2016, 41.7% of which was shared by the power industry [75]. Replacing fossil fuels with municipal waste will reduce emissions, which can be estimated by the following Eq. (11): [76]

$$ER_d = E \times (PE^1 \times Em_p^1 + PE^2 \times Em_p^2 + \cdots + PE^n \times Em_p^n) \quad (11)$$

Here Em is the emission factor and PE is the percentage of energy produced by each fuel. Table 3.4 contains emission factors for particular fuels. It indicates how many tons of harmful gases are generated for each MWh of generated electricity.

Table 3.4:

Emission factors [4]

Fuels	Emissions factor (ton/MWh)			
	CO_2	SO_2	NO_x	CO
Coal	1.18	19×10^{-3}	5.2×10^{-3}	0.2×10^{-3}
Petroleum oil	0.85	16.4×10^{-3}	2.5×10^{-3}	0.2×10^{-3}
Natural gas	0.53	0.5×10^{-3}	0.9×10^{-3}	0.5×10^{-3}
Hydro	00	00	00	00

On the other hand, vehicles transporting raw materials will generate emissions which are calculated by the following Eq. (12): [5]

$$ET = (M_f \times D \times EF_t)/TT_l \quad (12)$$

D is the hauling distance in kilometers. For our study, it is assumed 30 km as the existing dumpsite in Dhaka city is 30 Km away from the city [77]. Classification of vehicles, according to gross vehicle weight, is presented in Table 3.5. Garbage collection trucks are used, which are classified as vehicle type VII. The weighted average truckload per trip in tons in Dhaka is 7.8 tons on average [78]. The emission factor per kilometer is presented in Table 3.6.

Thus, the emission reduction using an incineration WTE conversion power plant was found from the following equation. Here E_b is the GHG emission intensity, which is considered to be 0.045 $kgCO_2eq/kWh$ [79].

$$E_e = ER_d - E_b - ET \quad (13)$$

Table 3.5

Classifications of the vehicles [5]

Class	Mass unit (ton)	Type of vehicles
IIb	3.86-4.54	Full-size pickup trucks
III	>4.54-6.36	Enclosed delivery trucks
IV	>6.36-7.27	City delivery trucks
V	>7.27-8.86	Large walk-in delivery trucks
VI	>8.86-11.82	Rack trucks
VII	>11.82-15.00	Garbage collection trucks
VIIIa	>15.00-27.27	Long-haul semi-tractor trailer rigs
VIIIb	>27.27	Double long-haul semi-tractor trailer rigs

Table 3.6

Emission factors of vehicle class VII [5].

Pollutant	Unit	Vehicle class VII
CO_2	ton/km	1.612×10^{-3}
NO_x	ton/km	4.64×10^{-6}
CO	ton/km	1.068×10^{-6}

Part-II

3.6 Municipal solid waste (MSW) collection projection

The first approach of determining the energy content in MSW and a suitable WTE technology is to quantify and qualify the amount of generated waste in the study are. But the actual amount of generated waste is never known. The actual amount of generated waste was assumed based on the amount of collected waste. In the annual waste report (2017) published by the Dhaka city corporations (DNCC & DSCC) indicates, the per capita waste collection is 0.56 kg per day for DSCC and 0.513 kg per day for DNCC[67][80]. For our research, MSW generation projection over 30 years period (2018-2048) for both DNCC and DSCC were estimated. This estimated projection was based on the historical waste collection data derived from the annual waste reports published by the city corporations and the district statistics data of Dhaka city published by the Bangladesh BUREAU of statistics[81][67][80]. The historical data used in the calculation is shown in **Table 3.1**. The amount of generated waste in any area is a population function while the composition of the waste depends on the income level of the population under study, the culture and tradition of that region, consumption pattern, and the ambient condition with the seasonal variation[82][83][84]. To estimate the waste projection different mathematical models have been proposed by different authors such as the Arithmetic projection model, Logistic Growth Model, Decreasing growth rate model[85][86][32]. In our research, logistic model has been considered to predict the MSW collection, equations (14)-(18) [87].

$$K_s = \frac{2 \cdot P_0 \cdot P_1 \cdot P_2 - P_1^2 (P_0 + P_2)}{P_0 \cdot P_2 - P_1^2} \tag{14}$$

$$Pop = \frac{K_s}{1 + ce^{a(t-10)}} \tag{15}$$

$$a = \frac{\ln\left[(P_0(K_s - P_1))/(P_1(K_s - P_0))\right]}{t_2 - t_1} \tag{16}$$

$$c = \frac{K_s - P_0}{P_0} \tag{17}$$

$$W_t = I_W \cdot Pop \cdot 365/1000 \tag{18}$$

In the presented model K_s indicates a saturated value. a and c are the logistic model constant. P_0, P_1, P_2 indicate the historical data of population to be used for the prediction and t_0, t_1, t_2 are the corresponding years. In this paper, to determine the collected municipal solid waste most recent MSW collection data reported by both of the city corporations on their annual waste report had been used. t is the year on which the amount of collected waste is to be predicted. W_t is the amount of waste collected in year t. I_W is the per capita waste generated per day. For Dhaka city the value is 0.875 kg/day [88].

3.7 Landfill gas (LFG) production

The landfill is a diffuse source of LFG gases rather than a point source as LFG gases are emitted throughout the different segments of the disposed waste. The generation of LFG gases shows variability in nature as different environmental parameters carve the LFG generation's biochemical procedure [89]. Besides, chain reactions and parallel reactions occur during the transformation process of degradable waste [89]. Therefore, it is not easy to determine the generated amount of LFG gases in a landfill as the full model tends to show complexity and variability with the environmental condition. Based on different laboratory and field inspections Single-phase and multi-phase kinetic empirical models have been developed over the years to estimate the LFG generation capacity of a landfill [53] [90]. The zero-order kinetic model assumes that all the potential LFG is emitted during that waste's deposition year [53]. The models based on the First Order Decay approach assume that at a stable environmental condition, the organic fraction of the waste disposed of in the landfill decays slowly throughout few years to few decades, and during this degradation process, LFG gases are produced. This LFG generation solely depends on the degradable carbon remaining on the disposed waste. So, LFG generation is higher during the first few years of the decomposition, then a gradual decline is seen as the amount of degradable carbon declines in the waste[53]. However, the uncertainty in the empirical model's parameters based on the second-order kinetic tends to have an adverse effect on the model's overall accuracy [91]. IPCC(1996) has recommended a mass balance method and first-order decay method to estimate LFG gas generation at the national level but was never designed to apply at individual landfills [92]. Recent studies suggest that first-order decay shows better accuracy than a simple mass balance model and is considered to have the required accuracy in estimating the entire country's LFG emission [53]. LFG gas production combined with extraction efficiency, the Fraction of Methane in landfill gas, the oxidation factor of the cover of the landfill, and the amount of CH4 emitted during the LFG extraction process enable the calculation of methane extraction as [93]:

$$CH4ex = \sum_{t=1}^{n} CH4_{gen,t} - CH4_{em,t} \times (1 - OF) \times \eta_{col} \times \eta_{ex} \times \mathrm{F}$$

$CH4_{ex}$ = Aggregated amount of extracted CH4,Gg

$CH4_{gen,t}$ = Generated amount of CH4 in year t, Gg

$CH4_{em,t}$ = Amount of CH4 emission in year *t*, Gg

OF = Oxidization factor

Most of the disposed waste generates LFG gas with a CH4 concentration of around 50%. Only those materials, including substantial oil or fat, can generate LFG gas with a CH4 concentration higher than 50% [91]. The key parameters involved in the LFG production from the disposed waste are half-life ($t_{1/2}$), Methane formation rate constant (k), Methane production potential (L_0), the amount of degradable organic carbon (DOC), the fraction of decomposable carbon present in the degradable organic carbon (DOC_f) and the oxidization factor of the cover material (OF).

3.7.1 Degradable Organic Carbon (DOC)

The empirical models to predict the LFG generation have an input parameter termed as Degradable Organic Carbon (DOC). This parameter indicates the fraction of degradable organic carbon present in the disposed waste. And only this degradable organic carbon is approachable for degradation using the biochemical procedure. DOC can be determined as [94][95]:

$$DOC = \%C_{Food\ Waste} \times \%W_{Food\ Waste} + \%C_{Paper} \times \%W_{Paper} + \%C_{Wood} \times \%W_{Wood} + \%C_{Textiles} \times \%W_{Textiles} + \%C_{Plastics} \times \%W_{Plastic} \quad (19)$$

%C indicates the fraction of organic carbon in a specific type of disposed waste, and %W indicates the mass fraction of that particular waste type in landfill. %C is determined using the ultimate analysis of the waste reported by several authors and presented in Table 3.7. The inert materials and recyclable materials such as metals, rocks, plastics, textiles, papers and dust was discarded during the calculation.

Table 3.7: DOC (Degradable organic carbon)

Food waste	0.15
Garden waste	0.2
Waste paper	0.4
Waste wood and straw	0.43
Textile’s waste	0.24

3.7.2 The Fraction of Decomposable Degradable Organic Carbon (DOC_f)

Some of the carbon present in the waste never degrades or degrades very slowly under Landfill’s anaerobic condition. The Fraction of Decomposable Degradable Organic

Carbon (DOC_f) is an estimated amount of carbon fraction, only which will be ultimately degraded by releasing LFG gases. A fraction of DOC is leached from the LANDFILL, but the fraction is negligible, disregarded during LFG generation calculation. Similar to DOC, the value of DOC_f of waste is determined by applying the assumption that the degradation process of different wastes is not dependent on each other. DOC_f is obtained according to[95][96] using:

$$DOC_f = 0.014 \times T + 0.28 \tag{20}$$

T indicates the landfill's temperature in Celsius. The value of DOC_f ranges between 0.42 to 0.98 for a temperature range between 10° Celsius and 50° Celsius. The temperature is assumed to be 27° degrees Celsius in the LANDFILL, the annual mean temperature of Dhaka city [97].

3.7.3 Methane production potential (L_0)

The methane production potential L_0 is the parameter that reflects disposed waste's capacity to produce methane throughout its life-cycle [98]. Methane production potential (L_0) is affected by the amount of DOC present in the landfill, DOC_f, microbial application rate, mean average temperature, and mean average perception in the landfill [99]. L_0 is empirically obtained as [100].

$$Lo = \left[\frac{G(0) \times 10^3}{\rho}\right] \times W \tag{21}$$

W is the Mass of the disposed waste in the LANDFILL in tons. ρ is the methane density, 0.717 kg/m^3. The value of G(0) is obtained as:

$$G(0) = W \times MCF \times DOC \times DOCf \times F \times \left(\frac{16}{12}\right) - R \times (1 - OF) \tag{22}$$

Where F is defined as volumetric methane fraction in LFG gas taken as 50% [100]. R is the methane recovery efficiency taken as 55.5% [86]. According to IPCC(2006), the methane generation potential ranges between 100 m^3/tons to 200 m^3/tons [93].

3.7.4 Half-Life ($t_{1/2}$) and Decay Rate (K)

The half-life is the amount of time required for a material to decay to half of its initial Mass. However, in the case of the disposed waste, the half-life indicates the amount of time required for the decomposable degradable organic carbon to decay to half of its initial mass. Different field studies on developing countries in tropical conditions suggest that approximate half-life values range between 3 years to 35 years, depending on the waste category [101]. The half-life range of MSW ranges between 4 years to 10 years [102]. In the First Order Decay approach formula to estimate the LFG generation from the landfill, a constant K is used, which is termed as Decay Rate. The relation between the Decay Rate and the Half-Life is formulated as:

$$K = \frac{\ln(2)}{t\frac{1}{2}} \tag{23}$$

Highly degradable waste shows a rapid decay rate, and under dry environmental conditions, slowly degradable waste shows a slower decay rate. According to the degradation rate, waste is categorized into three: Slowly degrading waste, Moderately degrading waste (non-food organic waste and putrescible domestic waste), and Rapidly degrading waste (Food waste, Sewage sludge) [93]. In Table 3.8 values of half-life and decay rate for tropical wet and moist environment condition is presented [93]. Dhaka has a mean annual temperature of 27^0. Moreover, mean annual precipitation ranges between 1400 mm to 1500 mm [97]. So Tropical, Moist, and Wet environmental category were considered for Dhaka. The decay rate used in this research was determined by using the weighted average method, which is used in several literatures [103][98]. The approximate value of the decay rate for Dhaka is determined as:

$$K = K_{Food\ Waste} \times \%W_{Food\ Waste} + K_{Paper} \times \%W_{Paper} + K_{Wood} \times \%W_{Wood} + K_{Textiles} \times \%W_{Textiles} + K_{Plastics} \times \%W_{Plastic} \quad (24)$$

Table 3.8

Half-life and decay rate

Waste categories		*Decay Rate(K)*	Half-Life($t_{1/2}$)
Slowly degrading waste	Waste paper and textiles waste	0.07	10
	Wood, straw, and Garden Waste	0.035	20
Moderately degrading waste	Non - food organic putrescible waste	0.17	4
Rapidly degrading waste	Food waste and Sewage sludge	0.4	2

3.7.5 Oxidization factor (OF)

A fraction of generated LFG is oxidized by the cover material used in the landfill. Methanotrophic micro-organisms present in the cover material can oxidize Methane from a negligible range to 100 percent [104]. The amount of LFG oxidization is affected by the cover material's thickness, moisture content, and physical properties. Well covered, sanitary landfill inclines towards the higher value of oxidization factor than the unmanaged or open landfill [104]. In Table 3.9, value**s** of oxidization factor based on the types of landfill is presented. Our study has considered a well-managed sanitary landfill, so the value of the oxidization factor of 0.1 is justified. This value will justify neutralizing both the cover material's oxidization effect and the escape of gases through the cover material's cracks.

Table 3.9

Oxidation Factor (OF) [93]

Landfill management policy	Oxidation Factor (OF)
Managed, unmanaged, and uncategorized landfill	0
Managed and covered with CH4 oxidizing material	0.1

3.7.6 Time delay

Under the waste management system of Dhaka city, waste is disposed of on the landfill continuously on a daily basis throughout the year. However, the production of LFG does not start immediately. During the decomposition process, the waste passes through different microbial reaction stages composed of aerobic decomposition and acidification. After that, when neutral conditions are obtained in the disposed waste, CH_4 production starts [92]. This uncertain delay between the deposition of waste and the LFG production's initialization varies with the environmental condition and the disposed waste's physical properties [104]. Following the IPCC guideline, we assumed our time delay of 6 months.

3.7.7 Methane correction Factor (MCF)

The methane correction factor (MCF) is an indicator of the management policy of the landfill. This factor is based on the fact that an unmanaged landfill will produce less LFG than a well-managed landfill. IPCC (2006) has categorized landfill as Managed-anaerobic, Managed-semi-aerobic, Unmanaged-deep (>5m depth of waste with or without high water table), and Unmanaged-shallow(<5m depth of waste)[93]. The corresponding MCF for each type of landfill management policy is described in Table

3.10 [93]. In Dhaka city corporation, existing landfill has a waste depth greater than 5 m [2]. However, as we considered well-managed-anaerobic landfill, so the MCF value one is justified.

Table 3.10

Methane Correction Factor (MCF)

Landfill management policy	Methane Correction Factor (MCF)
Managed – anaerobic	1.0
Managed - semi-aerobic	0.5
Unmanaged - deep (>5 m waste)	0.8
Unmanaged - shallow (<5 m waste)	0.4
Uncategorized landfill	0.6

3.7.8 IPCC model to estimate LFG generation from landfill

By determining the empirical relations between these parameters, most of the existing mathematical models and software packages are developed to determine Landfill’s LFG gas production capacity. In this research, the First-order Decay model proposed by IPCC was used to determine landfill's LFG gas production capacity [105]. This LFG generation estimation model is validated on the data of municipal solid waste. So, the models will give less accurate results for a circumstance when the waste contains less amount of organic material. In this research, we have discarded the recyclable portion of MSW.

$$R_{CH4} = \sum_{x=S}^{T-1} \{MSWT_x \times MSWF_x \times L_{0,x}(e^{-k(T-x-1)} - e^{-k(T-x)})\} - \frac{Q_{CH4}}{(1 - OF)} \quad (25)$$

Where,

Q_{CH4}= Emitted CH4 (Gg/year)

$MSWT_x$= Quantity of collected MSW in year x (Gg/year)

$MSWF_x$= Fraction of collected MSW landfilled in year x

T= Inventory year for which CH4 emissions were calculated

x= Year in which waste was landfilled

S= Start year of inventory calculation

R_{CH4}= Recovered methane (in Gg/year)

3.8 Quantification of Biogas production from the sewage treatment plant

Based on the population prediction results and per capita sewage generation data of Dhaka city, the amount of sewage production was calculated using Von Sperling's methodology [106]. This sewage calculation methodology uses per capita water consumption (q) and the estimated coefficient of return (C), indicating the fraction of consumed water flow as wastewater. The respective values of these parameters are 83.17 L/person/day and 85%, according to the research conducted on the sewage characteristics of Bangladesh [107]. For the calculation of total sewage flow, the amount of generated effluents was calculated. Effluents of all characteristics irrespective of the source of generation were considered. Equations (26)-(28) were used to anticipate the amount of sewage flow in Dhaka city.

$$Q_{WW} = \frac{(P_{served} \cdot q \cdot C)}{1{,}000} \tag{26}$$

$$Q_{inf} = \frac{(T_{xi} \cdot L \cdot 86{,}400)}{1{,}000} \tag{27}$$

$$Q_{\text{total}} = Q_{WW} + Q_{inf} \tag{28}$$

Q_{ww} = The average drainage of domestic sewage (m^3/d); Q_{inf} = Infiltrated sewage (m^3/d); Q_{total} = Total flow of sewage available for treatment(m^3/d). P_{served} = Population under the service area. T_{xi} = Infiltration rate per km of sewer line per second, adopted value was 0.3 [106].

The population under the service area (P_{served}) indicates that the number of inhabitants has a proper sewerage system connected to the sewage treatment plant. The existing sewerage facilities of Dhaka city is not sufficient. The current sewerage system has the capacity to serve about 30% of the total population of Dhaka [107]. P_{served} was estimated based on the projected population of Dhaka city multiplied by the fraction of inhabitants having the proper sewerage service. Q_{inf} was estimated by multiplying the infiltration rate with the dimensions of the sewage collection network. In Dhaka city, the existing sewage collection system has 881 Km of the service line [108]. The Biochemical Oxygen Demand (BOD) present in the sewage was estimated using equation (29)[107].

$$C_{BOD} = 1000 \cdot \frac{B}{Cq} \tag{29}$$

C_{BOD}= BOD present in the sewage (ml/L). B = BOD contribution of per inhabitants per day in grams. The value adopted for B is 40 g/inhabitants/day[107]. A value of 2.05 was adopted as the BOD/COD ratio to estimate the sewage's Chemical Oxygen Demand (COD).

The rate of methane production (m^3/day) was calculated using equation (30). Chernicharo developed this theoretical model assuming a reduction in oxygen demand over time for the organic matter breakdown process under aerobic conditions. Many authors used this mathematical model to predict methane generation under aerobic conditions [6][109][85].

$$Q_B = Q_{WW} \frac{[S_0(1 - Y) - S]}{f(T) \cdot C} (1 - I_L) \tag{30}$$

Here Q_B = The volume of biogas production per day from the sewerage treatment plant (m^3/day); S_0 = Affluent COD concentration (Kg/m^3); a value of 0.715 (Kg/m^3) was adopted for this research; S = COD concentration of the sewage (KgCOD/m^3); The adopted value of S was 0.251 Kg/m^3[85]; Y = Solid production coefficient; a value of 0.17 kgCOD sludge/KgCOD is adopted[85]; C = Methane concentration on generated biogas; a value of 65% was adopted. I_L= Rate of gas loss through the leakage or due to absorption in the sludge ; a value of 40% is adopted; f(T) = Volumetric conversion factor of Methane for a corrected temperature; estimated using equation (31)[85].

$$f(T) = \frac{P \cdot K}{R \cdot T} \tag{31}$$

A value of 300 k was considered for the value of ambient temperature, and 1 atm was considered for the value of atmospheric pressure. K= Required COD in grams to produce 1 mol CH_4; R = Gas constant. The constants K and R values were considered 64 gCOD/mol and 0.08206 atm l/mol k, respectively [85].

3.9 Energetic calculation of Bio-gas

Finally, the availability of power and energy from the collected methane can be calculated using equations (32)(33)[6]

$$\mathrm{P} = \mathrm{Q} \cdot \eta \cdot \mathrm{C}_{\mathrm{CH_4}} \cdot \mathrm{LHV} \tag{32}$$

$$\mathrm{E} = \mathrm{P} \cdot \mathrm{F_C} \cdot \Delta\mathrm{t} \tag{33}$$

Here, Q= Total flow of collected gas. P= Available power (MW); E = Availability of energy annually (MWh/y); Δt= Operating time of the power conversion system per year (h/y); η = Efficiency of the power conversion system; a value of 33% was adopted which is the power conversion efficiency of internal combustion engines [110] and LHV = Lower heating value. The adopted LHV value is 35.5 MJ/m^3. When gas is collected from Landfill, it has a 50% methane index [86]. The corresponding value of the methane index is 65% when gas is collected from the sewerage treatment plant [86]. The methane index designates the fraction of methane in gas. F_C indicates the capacity factor for power generation plant. Capacity factor indicates the ratio of annual power generated by the plant to the maximum power generation capacity of the plant. The maintenance break and the variation in the power output is considered under this parameter. In this research the adopted value of F_C is 83.3% according to the proposal of [6].

3.10 Optimum power and energy generation from landfill

The methodology used in this research to determine the optimum power and energy output from the landfill of Dhaka city was proposed by Santos and Barros [111]. In the proposed methodology, the power generation capacity to be installed under consideration for a single power generating unit to maximize energy production and the optimum number of power generating units was determined. This methodology consists of a calculation that resembles the power output combined with the duration of LFG availability. As the number of power generating units increases, the total energy production gets higher. However, with the increase in the number of power generating units, the capital cost also increases. Based on the retrieved outcomes, it was settled that for the most optimum economic performance, a maximum number of three generators could be used [111]. According to the research conducted on gas engines, a decay in gas turbine performance was observed when operating at partial load conditions. The gas turbine's power output decreases up to 10% when operating at a 60% load rather than 100% [111]. Considering these results, assumptions were made such that the power extraction capacity from the landfill will be escalated by installing additional power generating unit up to the optimum number of powers generating unit and the power generating unit only works when they are supplied with the required amount of LFG to operate at 100% load.

3.11 Calculation of emission mitigation by relocated energy

When fossil fuels are combusted to produce electrical energy, an adverse global warming effect is witnessed. The utilization of biogenic gas can diminish this adverse effect. So, the emission factors for the biogenic gas-based power plant are negligible compared with fossil fuel-based power plant. Under this consideration, several authors have assumed the emission factor's value to be zero[112][113]. The estimated emissions avoided by utilizing biogenic gas for electricity generation were calculated by multiplying the energy production with the grid emission factor for Bangladesh (Equation(34))[112].

$$E_v = E \cdot E_f \tag{34}$$

Here E_f indicates the grid emission factor for Bangladesh (0.67 tCO_2/MWh)[17]. E_v indicates the quantity of avoided emission tCO_2/year.

3.12 Comparison between LFG and Biogas

To determine the relationship between unit power output per inhabitant, a dimensionless parameter λ was proposed by [62], which is represented by equation (35).

$$\lambda = \frac{P_{\text{Landfill}}/P_{Op}}{P_{WWTP}/P_{Op}} \tag{35}$$

3.13 Utilizing biogenic gas in the transportation fleet

The possibility of using biogenic gas in the municipal transportation fleet in place of fossil fuel was also analyzed in this research. The number of transportation units possible to supply with the generated biogenic gas, CO and NOx emission avoided compared with Diesel fueled transportation system was determined. The parameters used in this calculation are presented in Table 3.11.

Table 3.11

Parameters used in the calculation for the transportation fleet [6]

Parameter	Value	Source
Biogas Consumption in m^3/km	0.45	[6]
Transportation route in km/day	120	Adopted
NO_x emissions per km	Biogas bus-2.25g	[6]
	Diesel bus-11g	[6]

3.14 Economic analysis

The cost of different equipment types considered in different scenarios was aggregated to find the Power Plants' total construction cost. To analyze the economic feasibility of different scenarios, Net Present Value (NPV), Levelized Cost of Electricity (LCOE), Profitability Index (PI), Internal Rate of Return (IRR), Modified Rate of Return (MIRR), Payback Period (PBP) were analyzed. These economic parameters are defined in equations (36)-(39). The positive NPV value indicates the investment's economic viability, whereas the negative NPV value indicates the infeasibility of the investment, resulting in losses. According to IRENA 2015, LCOE is considered the most common economic indicator that enables cost comparison of generated electricity utilizing different power generation technologies. LCOE indicates the least energy selling rate to secure economic viability from the venture.

IRR indicates the value of interest (i) that will cause the NPV null. The IRR value was determined using the trial and error method as it cannot be found using the analytical process. PI is another standard economic indicator used in the financial analysis of a public project. It is indicated by the ratio of the present value of payoffs and the initial investment. PBP designates the number of years required to recover the initial investments.

$$\text{Net Present Value } (NPV) = I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + LEX_t)}{(1+i)^t} \tag{36}$$

$$\text{Internal Rate of Return } (IRR) \rightarrow \; NPV = I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + LEX_t)}{(1+i)^t} = 0 \tag{37}$$

$$\text{Profitability Index } (PI) = \frac{\text{Present Value of payoffs } - \sum_{t=1}^{n} \frac{(OMEX_t + LEX_t)}{(1+i)^t}}{I_0} \tag{38}$$

$$\text{Levelized cost of Electricity } (LCOE) = \frac{I_0 + \sum_{t=1}^{n} \frac{(OMEX_t + LEX_t)}{(1+i)^t}}{\sum_{t=1}^{n} \frac{(E_t)}{(1+i)^t}} \tag{39}$$

3.15 Assumptions for the economic analysis

3.15.1 Economic life cycle

According to IRENA 2012, a typical WTE conversion power plant's economic life cycle varies from 20 to 25 years [114]. This research assumed 25 years of the life cycle for the WTE conversion power plants starting from 2021 with a construction period of 4 years. Therefore, the power plants will be operational in the year 2025.

3.15.2 Depreciation Characteristics

A constant depreciation characteristic with a zero-salvage value was considered in this research, starting from the beginning of the power plant's operational period.

3.15.3 Waste and transportation cost

In this research, we have assumed the power plants to be a public venture and to be operated by the state-owned power generation and development corporation BPBD. Therefore, the cost of waste was neglected, and it was considered available throughout the power plant's life cycle. The waste transportation cost was discarded in this research to compare the WTE technologies after the waste is delivered to the power plant's waste handling facility.

3.15.4 Electricity selling tariff

In this research, we have assumed the electricity selling tariff in accordance with the Flat retail tariff rate for the Bangladeshi market, which is 70 USD/MWh [115]. A realistic value of 2.5% annual inflation rate was considered in this research for the electricity selling tariff.

3.15.5 Weighted average capital cost (WACC)

In this research, we have assumed the WACC in accordance with the optimistic value encouraged for a power plant, which is 7% [111].

3.15.6 Capital Expenditure

Capital cost includes planning and construction cost. Construction cost includes constructing a waste handling unit, a Source separation unit, a power generating unit, and the components used to transport the generated gas and energy. The construction cost of the components related to both of the WTE conversion plants is summarized.

3.15.7 Annual waste handling capacity and throughput to the WTE conversion plants

For this research, we assumed a waste handling unit operating at a capability of handling 1000000 tons of feedstock. This waste handling unit is assumed to be installed for both of the WTE conversion technology. It was also considered that the waste handling unit is performing at an 85% capacity factor. So annually, 8500000 tons of feedstock will be delivered to the WTE conversion facilities.

Around 18% of the generated MSW is considered to be recyclable under the waste characteristics of Dhaka City. So out of 1000000 tons of raw MSW, around 180000 tons has the potential to be recycled [1]. The selling price of recycled metal is assumed to be 0.03 USD/kg[12]. The accepted selling price is 0.02 USD/Kg for recycled paper, and for recycled textiles and plastic contents, the assumed price is 0.08 USD/KG[12]. 9000 USD/ton revenue can be generated by selling the recycled contents totaling around 9000 million USD annually from the waste delivered to the landfill. Recycling potential was discarded from the sludge delivered to the sludge treatment facility as sludge contains a higher organic fraction with negligible recycling potential [107].

The feedstocks were treated at the pre-treatment facility to increase the WTE conversion technologies' efficiency. All of the recyclables were assumed to be separated at the pre-treatment facility.

3.15.8 Residual feedstock landfilling cost (LEX_t)

A typical WTE conversion facility that utilizes AD technology generated around 15% residual[12]. This research assumes that the generated residual will be landfilled with a landfilling cost of 0.01 USD/KG[12].

3.15.9 The operating and maintenance expenditure for the WTE conversion plants (OMEX)

The OMEX for a typical WTE conversion power plant is classified into fixed OMEX and variable OMEX. The fixed OMEX includes labor cost, insurance cost, Routine equipment maintenance, and replacement cost. In contrast, Variable OMEX includes unscheduled equipment maintenance and replacement cost, fuel transportation, and residual disposal cost. According to IRENA 2015, the fixed OMEX can be expressed as the capital cost function, which varies between 3% and 6%. The variable OMEX depends on the power output and the capacity factor for a specific WTE conversion plant. For this research, we have assumed 5% capital cost as the variable OMEX in contrast, 4 USD/MWh as the variable OMEX.

3.16 Scenario Analysis

Under this research, four different scenarios had been investigated to compare alternative strategies to generate energy utilizing biogas generated from the sewage treatment plant and LFG from Landfills. Economic feasibility had also been analyzed to find the best approach under different scenarios.

3.16.1 Scenario 1

Under this scenario, biogas generated from the sewage treatment plant was considered only, discarding the power generation capacity from available LFG. A base power generation unit to be installed under this consideration. This output power(P_{base}) to be available throughout the economic life of the sewage treatment plant.

3.16.2 Scenario 2

Under this scenario, LFG generated from the landfill was considered only discarding the power generation capacity from available biogas generated in the sewage treatment plant. A single power generating unit was regarded under this consideration, which will maximize energy output. However, this output power (P_{me}) will be available only when the power generating unit is supplied with the LFG to operate under 100% load condition.

3.16.3 Scenario 3

In this scenario biogas generated from landfill was considered with more than one installed generators.

3.16.4 Scenario 4

In this scenario biogas generated from both landfill and sewage treatment plant was considered. For landfill plant only one generator was used.

3.16.5 Scenario 5

Under this scenario, the combined use of LFG generated from landfill and biogas generated from the sewage treatment plant was considered. Minimum base power (P_{base}) was considered for the sewage treatment plant, which was approximated to be available throughout its economic life cycle. Three power generating unit to utilize LFG was considered under this scenario. In this research, an escalation-based power installation model was considered, which is achieved by installing additional power generation unit rather than installing a single unit of higher capacity. Furthermore, the power generating unit under consideration operates only when supplied with LFG to operate at maximum load conditions. Under this consideration, there will be no power output up to 6000 kW. The first power-generating unit of 7500 KW will be installed at the year 2024. The total power generation capacity will be escalated utilizing an additional power generating unit of 5500 kW at the year 2035.

3.16.6 Scenario 6

Under this scenario, the combined use of LFG generated from landfill and biogas generated from the sewage treatment plant was considered similar to scenario 3. However, under this consideration, thermal and electrical combined energy generation was considered utilizing LFG. The recovered thermal energy used for the sludge drying, generated from the sewage treatment plant. The sludge drying system under consideration is based on the methodology proposed by [6], which utilizes a centrifugal dryer, followed by a conveyor type thermal dryer. Under this scenario, the additional construction and maintenance cost of the sludge drying equipment was added. The sludge disposal cost to the landfill was also added. The cost-saving due to the decrease in sludge volume is considered as revenue under this scenario.

The generation of LFG can be seen for many years from a specific landfill. However, to obtain a realistic energy generation scenario, a shorter time frame was considered in this research. The approximate distance between the sewage treatment plant and the landfill (Dhaka) is 8 Km. So, the piping length of 8 km was considered for scenarios 3 and 4 for scenarios 1 and 2, which is approximated as 500 m.

3.17 Sensitivity analysis

A sensitivity analysis was also conducted to obtain the range of variation when different independent parameters controlling the economic viability were varied. The variation in LCOE and LCOW was analyzed by varying the weighted average capital cost (WACC) parameter between 7% (optimistic value encouraged for a project) and 13% (very high optimistic value) [111]. WACC plays a significant role in determining the economic viability of a plant [6]. The sensitivity of NPV was also analyzed relating to the energy selling price varied between 70 USD/MWh (Flat retail tariff rate for the Bangladeshi market) and 106 USD/MWh (Retail tariff rate during peak demand in Bangladesh) [115]. The NPV results were also analyzed relating to the value of carbon credit per ton. The carbon credit value was varied between 0 USD/ton (Scenario discarding carbon credit) and 2.85 USD/ton (Optimistic value) [111].

Chapter 4: Result

Part-I

4.1 Energy analysis of the municipal solid waste

MSW can be used as a primary source of energy to run a small-scale bio-waste-based power plant. The molecular bond of the waste products contains chemical energy. When the waste products are passed through the energy extraction methods, e.g., Incineration, Gasification, Aerobic Digestion, the molecular bond breaks down and the energy gets released as thermal energy [116]. This released energy isn't always the same as it is dependent on several parameters like moisture content, organic carbon, volatile matter, density, ash content [5]. In Fig. 2**,** the relation between the moisture content and LHV is shown. As the moisture content of the waste increases, the LHV decreases linearly. This linear LHV decrease rate (decrease in moisture content for a 1% increase in moisture content) varies depending upon the waste type. The LHV decrease rate is maximum for plastic; in contrast, minimal LHV decrease rate can be observed for paper. The moisture content and LHV show a negative covariation. The MSW properties vary depending upon the ambient environment condition and the change in MSW generating area. Waste from a large urban city contains less food waste than waste from smaller towns [29].

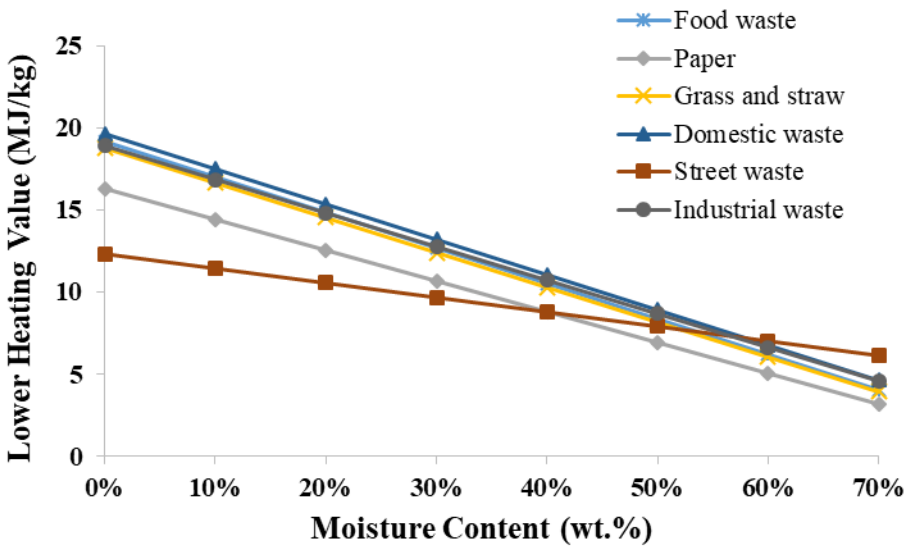

Fig. 4.1. LHV vs MC of MSW based on biomass fuel.

Organic and food waste make up the most considerable portion of MSW and higher moisture content is seen in this waste category. For food waste with 70% moisture content, the calculated LHV is 4.04 MJ/kg. This high moisture containing organic and food waste can cause several issues like causing erosion to the turbine blade. So, to deal with this problem, waste pretreatment is done. Pretreatment decreases the moisture content, improves the biomass fuel properties, and makes the waste denser, enabling safe handling from the source of waste collection to the incineration plant. In most cases, superheated vapor leaving the turbine outlet is used to pretreat the moist waste. The waste is collected in an unsorted manner. Some of the waste categories such as plastic and textile waste, contain a high heating value with low moisture ratios than organic and food waste. Fig. 2 shows that the LHV ranges between 19.64 MJ/Kg to 4.62 MJ/Kg with a moisture content ranging between 0% to 70% in domestic waste. For industrial waste, this LHV range is 18.91 MJ/Kg to 4.58 MJ/kg and for street waste 12.32 MJ/Kg to 6.14 MJ/Kg. Using the empirical equations, it is found that food waste contains 3.54 MJ/kg at 72% moisture content, plastic contains 41.78 MJ/kg at 0.53%

moisture content, paper contains 15.70 MJ/Kg at 3.20% moisture content, textile contains 28.44 MJ/Kg at 0% moisture content, grass and straw contains 10.66 MJ/Kg at 38% moisture content.

4.1.1 Fuel requirement for a 10 MW biomass-based power plant

The thermal energy produced during the MSW incineration process is used as the primary source of energy to run a BFB conversion system. 52 ton per hour capacity of the boiler is required to power the generator. 2.9 GJ heat input is needed to produce 1 ton of steam [5]. So, 150 GJ/h heat is required to run the boiler. The steam pressure at the outlet of the superheater of the turbine is 66 kg/cm^2 and the temperature is 465^0 C [117]. It is estimated that around 22.04 ton/h raw MSW (LHV 8.98 MJ/Kg) is required to power the boiler. Raw MSW contains around 41% moisture. If the moisture content is increased to 70% (LHV 4.91 MJ/Kg), the fuel requirement increases to 40.33 ton/h. If we consider food waste, which makes around 67% of total MSW, 55.93 ton/h raw food waste (LHV 3.54 MJ/kg) is required to power that 52 ton per hour capacity boiler. The raw food waste contains 72% moisture. The LHV gets increased by 197% and the fuel requirement is dropped by 40% by reducing the moisture content to 40%.

Fig. 4.2 indicates a positive correlation between moisture content and annual fuel requirement. The raw MSW requirement increases from 84944 tons to 266343 tons per year against a moisture content increase from 0% to 70%. Food waste requirement increases from 62132 tons per year to 294723 tons per year against a moisture content increase from 0% to 70%. Plastic, paper, and textile contain minimal moisture, varying between 0% to 10%, and their requirement to generate the same amount of thermal energy as food waste is considerably low.

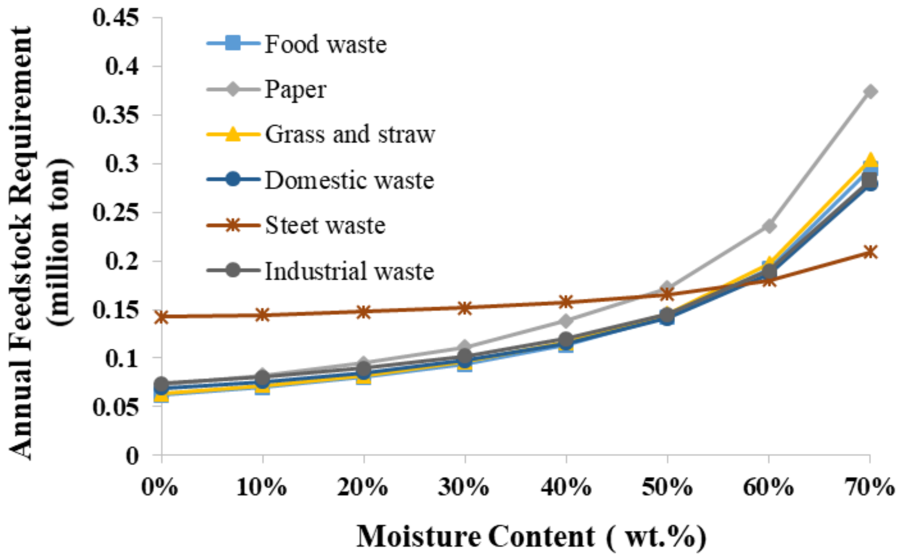

Fig. 4.2. Change of the required amount of biomass with efficiency

4.1.2 Impact of system efficiency on biomass requirement

The system efficiency range varies between 20% to 35% for a biomass-based thermal power plant [5]. The efficiency of the system depends on the scale and technology used in the power plant. A small-scale (<1MW) biomass power plant has a system efficiency of 20%, which goes up to 40% for a 20 MW biomass integrated gasification combined cycle (BIGCC) power plant [118]. The efficiency of the biomass-based power plant is highly correlated to the type of fuel used. As the fuel type changes, the amount of fuel required changes. For this study, we analyzed food waste, plastic, paper, grass, straw and textiles. Different fuels have different properties that can be improved by the pretreatment process, which requires additional investments. Fig. 4 describes the relationship between the required fuel annually and system efficiency. Annual fuel requirement decreased with the increase in system efficiency. When food waste is used as raw material, 378990 tons of raw food waste is required for a 20% efficient system. The requirement for raw food waste drops by 50% when the system efficiency is increased to 40%. Similarly, by increasing system efficiency from 20% to 40%, the fuel requirement drops by 16040 tons when plastic is used as fuel; in contrast, 42685 tons drop is observed for paper, 62843 tons for grass and straw, 21363.5 tons for textile products. But to consider a biomass-based power plant with more than 30% efficiency is not always applicable. But different studies indicate that higher efficiency is possible to achieve when BIGCC powered by fluidized bed boiler is used [5].

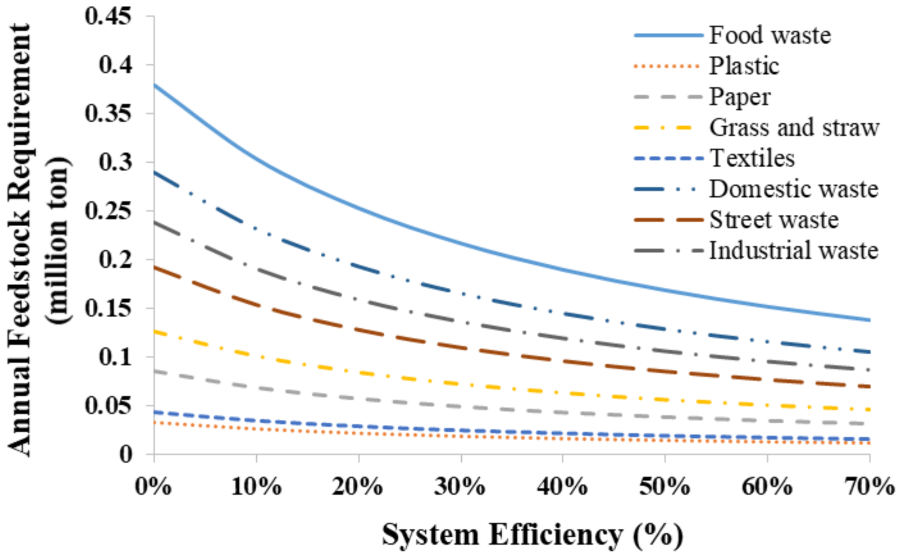

Fig. 4.3. The required amount of biomass for a 10MW system

4.2 Cost analysis

4.2.1 Impact of system efficiency on fuel cost

With the increasing system efficiency, the annual fuel requirement decreases, which led to a decrease in annual fuel cost. Fig. 5 describes the annual cost of domestic waste, industrial waste, street waste, food waste, paper, plastic, grass and straw, and textiles used as fuel to run a 10 MW biomass-based power plant when system efficiency is varied between 20% to 55%. The food waste cost as fuel is $ 2.13 million when the system efficiency is 20%, for plastic the price is $ 0.18 million, for paper $ 0.48 million, for grass and straw $ 0.71 million, for textile $ 0.24 million, for domestic waste $ 0.91

million, for industrial waste $ 0.77 million, for street waste $ 0.81 million. The price decreases with increasing system efficiency. The annual fuel cost is approximately $ 0.75 million when MSW is used in raw form without any pretreatment and drying process on a biomass-based power plant of 22.5% system efficiency. The price of raw MSW decreases from $ 0.845 million to $ 0.31 million when the system efficiency is increased from 20% to 55%.

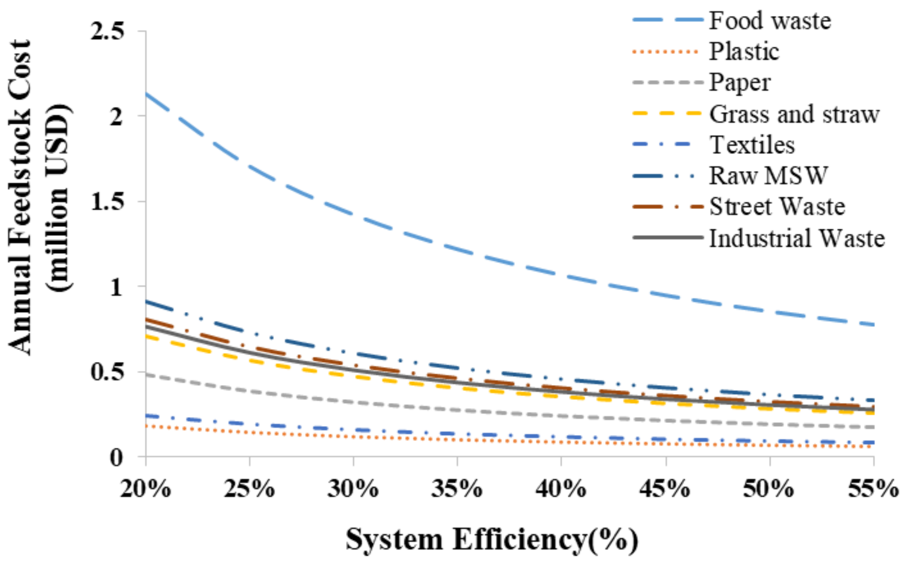

Fig. 4.4. Annual cost of waste vs System efficiency (%)

4.2.2 Impact of moisture content on fuel cost

With the increase in moisture content, the fuel requirement increases. This led to an increase in fuel cost to produce 10 MW power. The moisture content of municipal solid waste generally varies between 0% for non-degradable plastic and textile waste to 72.34% for organic biodegradable waste like food waste. The moisture content of raw municipal solid waste in this study is found to be 42.1%. The impact of moisture content on fuel cost can be seen in Fig. 6. When the moisture content is increased from 0% to 70%, the price of food waste as fuel is increased from $ 0.35 million to $ 1.66 million, a sharp $ 1.21 million increase; for plastic, this increment is around $ 0.46 million, for paper $1.70 million, for grass and straw $ 1.35 million, for textile $ 0.66 million, for the domestic waste $ 1.18 million, for the industrial waste $ 1.18 million and for the street waste $ 0.37 million. Similarly, when the moisture content of raw municipal solid waste is 0%, the fuel cost is $ 0.48 million, which increases sharply to $ 1.50 million with the increase of moisture content to 70%. Waste pretreatment process and drying can decrease the moisture content, which requires an additional rise of the initial cost to build a waste pretreatment plant.

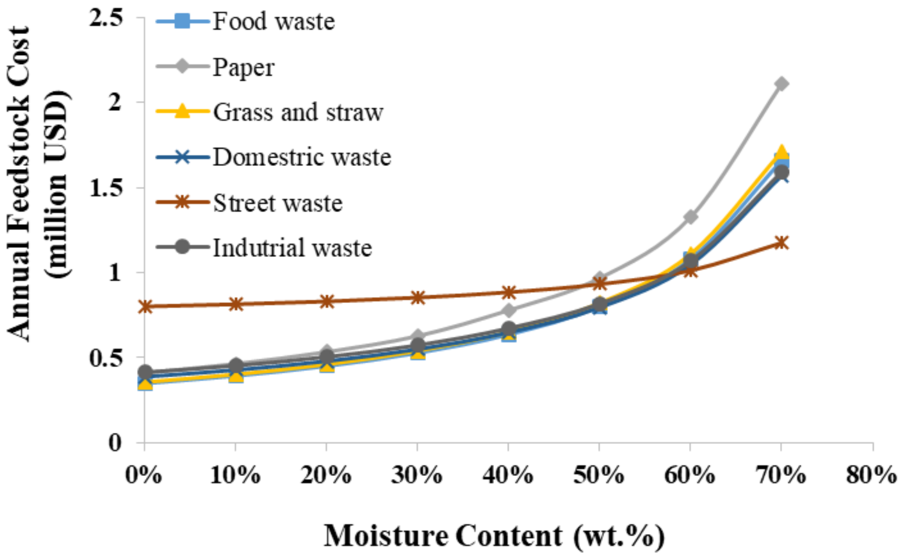

Fig. 4.5. Annual cost of fuel with varying MC

4.2.3 Impact of increment of system efficiency on fuel requirement and fuel cost

Fig. 7 describes the impact of increment of the system efficiency on fuel requirement (ton/year) for different types of waste used to run the power plant. When raw municipal solid waste is used as the primary fuel, 50700 ton/year fuel can be saved by increasing system efficiency from 20% to 25%. If we analyze the results, it can be seen that maximum saving for all types of waste occurs when the efficiency is increased to 25%

from 20%. 20% of fuel can be saved if we increase the system efficiency to 25% from 20%. In contrast, 16.67% of the fuel is saved by increasing system efficiency to 30% from 25%. There is little to no feasibility to increase the efficiency above 30% as the capital cost gets very high. It is more feasible to keep the system efficiency between 20% to 25% to run a small-scale biomass-based power plant. As the initial cost approximately increases by 78% if we try to improve the system efficiency from 20% to 40% (The Initial cost is 1400 USD/KWe for a small scale 20% efficient stoker boiler in contrast, for 40% efficient BIGCC, the initial cost is 2500 USD/KWe [60]).

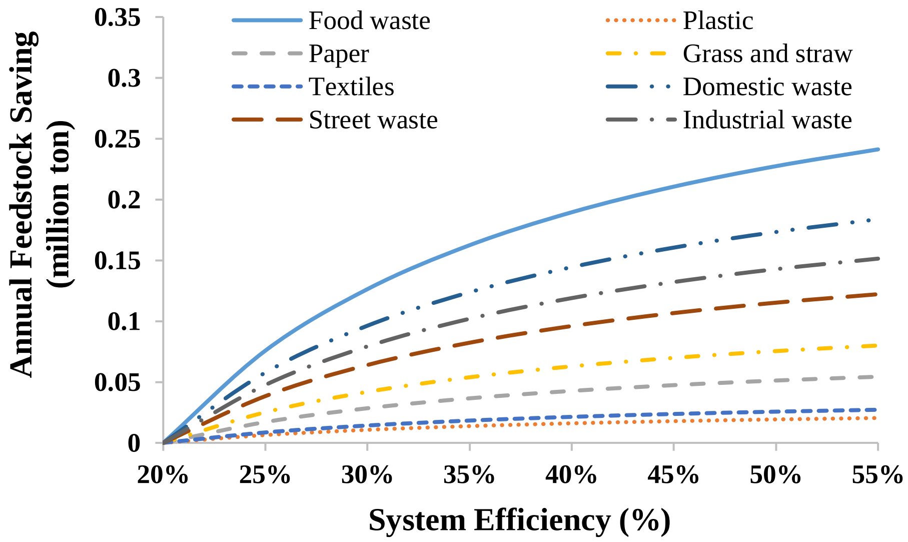

Fig. 4.6. Impact of system efficiency on fuel saving

Annual fuel cost savings is described in Fig 8. If we consider food waste as our primary fuel, a 5% (from 20% to 25%) increment in system efficiency saves 0.43 million USD yearly. When raw municipal solid waste is considered by increasing 5% (from 20% to 25%) system efficiency can save 0.285 million USD yearly. The comparative analysis indicates that through food waste is a low grade municipal solid waste to be used as a primary fuel to the biomass-based power plant; it saves more than plastic (saves 0.04 million USD), paper (0.1 million USD), grass and straw (0.14 million USD), textiles

(0.05 million USD) if we consider the same amount of increase in system efficiency (from 20% to 25%).

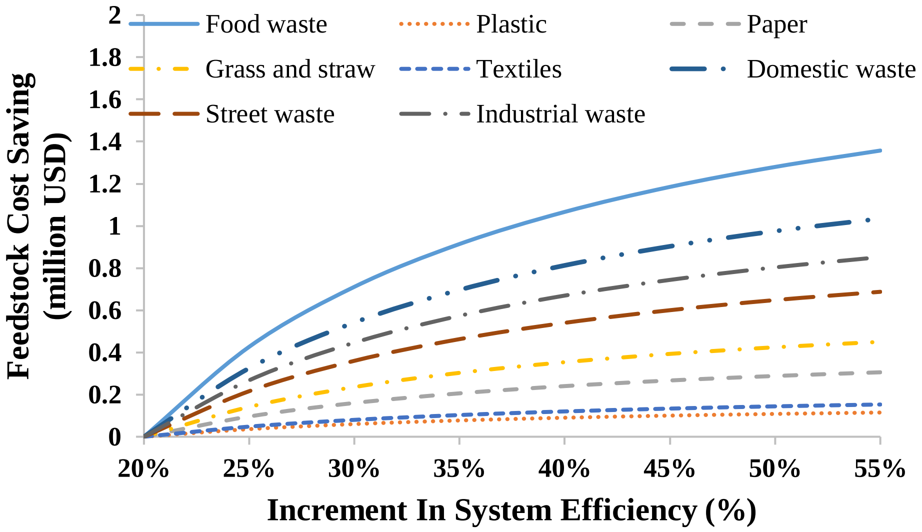

Fig. 4.7. Impact of system efficiency on fuel cost saving

4.2.4 Impact of increment of moisture content on fuel requirement and fuel cost

Fig. 9 illustrates the increase in the annual fuel requirement with respect to increased moisture content for different categories of waste used as the primary fuel in MSW based power plant. Annual fuel requirement increment is maximum when the moisture content increases from 60% to 70%. Raw MSW requirement annually increases by 190% when the moisture content increases from 50% to 70% and associated fuel cost increase by 0.705 million USD. When food waste is considered as the primary fuel, 20% (from 50% to 70%) increments in the moisture content increase fuel requirement by 190%, which is approximately 0.921 million USD yearly. The comparative analysis indicates that when plastic is used as the primary fuel in the biomass-based power plant, the increment in fuel requirement and associated fuel cost is less than food waste (190%

and 0.921 million USD), paper (205% and 1.2 million USD), grass and straw (191% and 0.96 million USD), textiles (163% tons and 0.44 million USD) if we consider the same amount of increase in moisture content (from 50% to 70%). But the moisture content of plastic and textile waste ranging between 50% to 70% is not reasonable. In our study, we found that the moisture content of plastic and textile ranges between 0% to 10%.

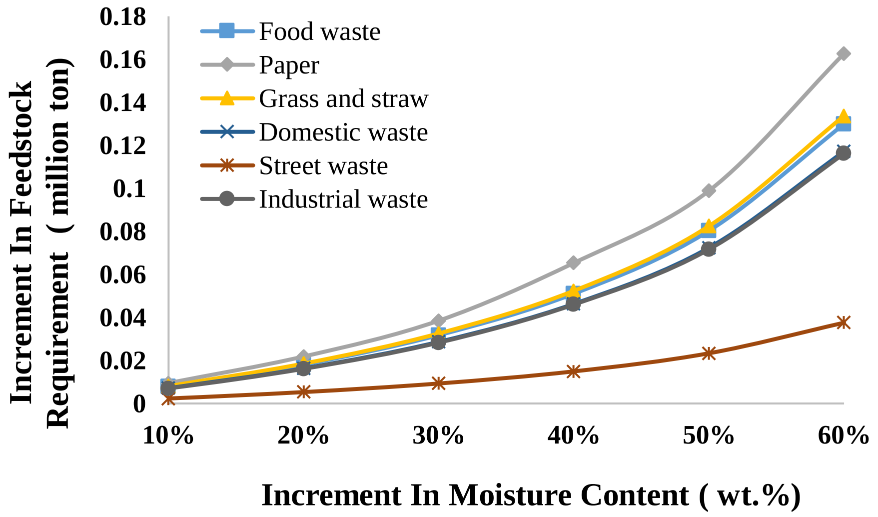

Fig. 4.8. Impact of moisture content on fuel requirement

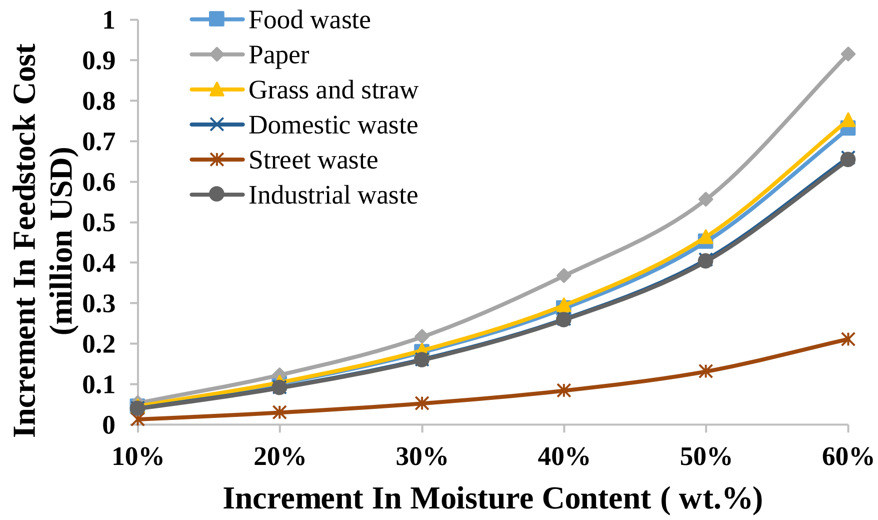

Fig. 4.9. Impact of moisture content on fuel cost

4.3 Financial model analysis

In this study, based on the stated assumptions, the financial model was assessed by evaluating the financial indicators, i.e., NPV, LCOE, LCOW, IRR, MIRR, payback period, and PI. The results of the financial indicators are described in Table 8. As shown in Table 8**,** incineration WTE conversion technology from Dhaka city's perspective shows feasibility according to its financial performance over the financial indicators. The positive NPV indicates that the financial profitability of incineration WTE conversion technology from Dhaka city's perspective, further strengthened by the obtained PI result as the obtained value of PI is greater than one. The payback period is also calculated for this financial model. The LCOE indicator indicates the minimum selling price of generated electricity from the incineration WTE conversion plant that would make the plant profitable under the assumption. Under the stated assumptions, there are no other sources of revenue from the proposed plant. The obtained value of LCOE indicates that under the present tariff rate in Bangladesh, this incineration WTE conversion plant will not be profitable. Similarly, LCOW suggests the minimum required revenue that must be earned from per ton of waste under the assumption that waste is the only fuel used in the proposed plant. The obtained IRR and MIRR are higher than WACC, which further indicates this incineration WTE conversion plant's financial profitability. The difference between IRR and MIRR is that for IRR, it is assumed that the net positive cash flow recovered from this incineration WTE conversion plant is reinvested at the IRR but for MIRR, which is reinvested at WACC. MIRR is considered to provide more accurate financial indications than IRR.

Table 4.1

Financial indicator

Net present value (NPV)	4,357,268 USD
Profitability index (PI)	1.11
Payback period (Years)	9.60
Levelized cost of electricity (LCOE)	0.12 USD/KWh
Levelized cost of waste (LCOW)	87.27 USD/ton
Internal rate of return (IRR)	11.1%
Modified internal rate of return (MIRR)	10.5%

4.4 Sensitivity analysis

A sensitivity analysis was carried out to find out the main factors affecting the financial model. To determine this sensitivity impact of input parameters on the investment criterion, capacity factor, capital cost, facility power generation capacity, WACC, and electricity tariff were subjected to change. The considered investment criteria were NPV, LCOW and payback period. The selected input parameters were varied between -5% to 5%. According to the sensitivity analysis, NPV shows the highest variation with the financial model's changing input parameters. On the contrary, the payback period and LCOW shows minimal variation.

4.4.1 Impact on NPV

The impact of the varying input parameters on NPV (in USD) is presented in Fig 11. The NPV shows a positive correlation with the changing capacity factor, electricity tariff rate, facility generation capacity but shows a negative correlation with the changing WACC and capital cost. The highest variation is observed for electricity and only a minor change is observed when facility generation capacity was varied.

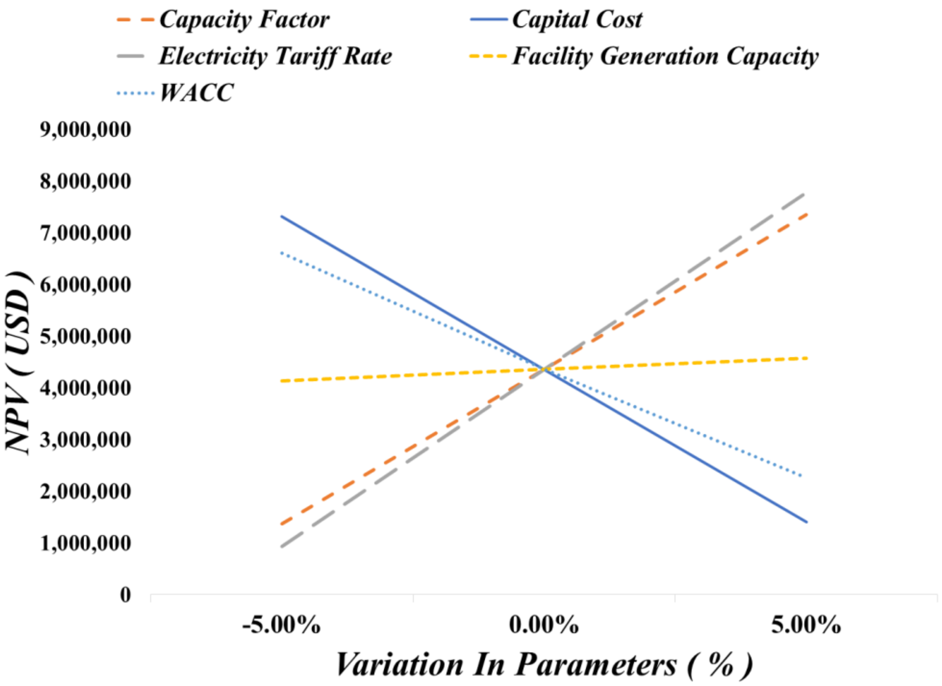

Fig. 4.10. Sensitivity analysis result for NPV

4.4.2 Impact on the Payback period

The sensitivity analysis results in the case for the payback period are presented in Fig 12. The payback period results indicate a positive correlation with the changing capital cost and the facility generation capacity but negatively correlated with the changing capacity factor and electricity tariff rate. The observed variation was highest for electricity tariff rate and lowest for facility generation capacity. The result also indicates that the changing WACC had no effect on the payback period.

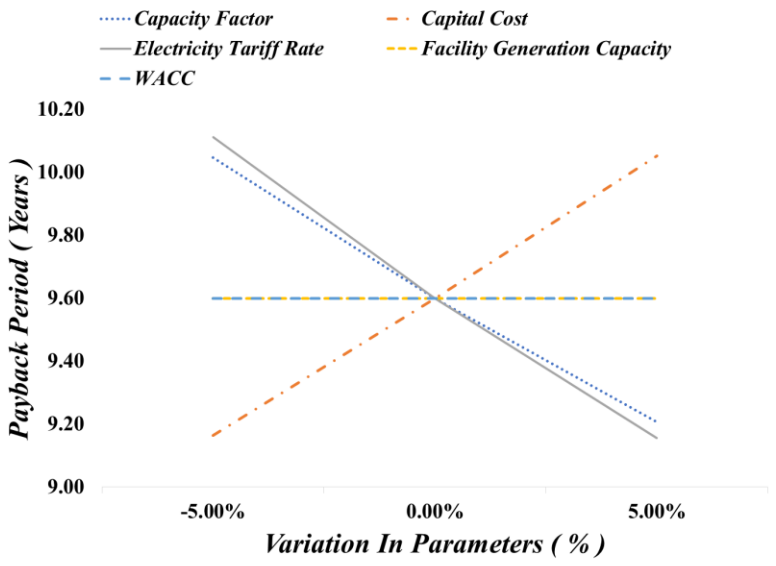

Fig. 4.11. Sensitivity analysis for the payback period

4.4.3 Impact on LCOW

The sensitivity analysis results in the case for LCOW are presented in Fig 13. The LCOW results indicate a positive correlation with the changing capital cost, WACC, and the facility generation capacity but show a negative correlation with the changing capacity factor. The observed sensitivity was highest for capacity factor and lowest for facility generation capacity.

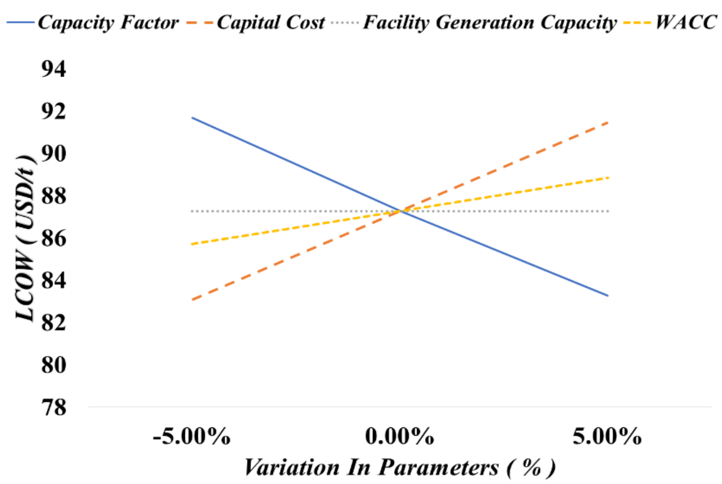

Fig. 4.12. Sensitivity analysis for LCOW

4.5 Environmental Impact assessment

The ratio between actual power output from a power plant and the hypothetical output it would generate if the plant could run at full potential is the capacity factor. A typical biomass power plant has a capacity factor of 85% [12]. At 85% capacity factor, a 10MW biomass power plant can generate 74,460 MWh/y. Replacing this amount of power from the generation mix of fossil fuels can reduce GHG emissions. Considering the change of generation mix over the years ([119], [120], [121]), emission reduction for the years 2020 and 2030 is presented in Table 4.1. The percentage share of coal is going to increase as more coal-based power plants are ready to run in the near future.

Table 4.2

Estimated reduction of emission at 85% capacity factor

Year	Energy Replaced (MWh)	CO_2 (ton/y)	SO_2 (ton/y)	NOx (ton/y)	CO (ton/y)
2020	74,460				
Coal (2.54%)		2232	26	10	0
N.Gas (54.84%)		21642	20	37	20
Oil (35.71%)		22601	436	66	5
ER_d		46475	483	113	26
ET		833		2	1
E_e		45642	483	111	26
Year	Energy Replaced (MWh)				
2030	74,460				
Coal (51.89%)		45592	537	201	8
N.Gas (36.06%)		14231	13	24	13
Oil (1.17%)		741	14	2	0
ER_d		60563	565	227	21
ET		833	-	2	1
E_e		59730	565	225	21

Table 9 shows that the reduction of emission of CO_2 will increase from 45778 tons in 2020 to 59975 tons in 2030, which is about a 31% increase in reduction over a period of 10 years. If we can increase the capacity factor, GHG emission will reduce further.

Part-II

4.6 Waste collection and available energy potential prediction

The annual waste collection projection is presented in **Fig. 4.13.** The amount of waste collection is a waste generation function. But as the actual amount of generated waste is never known so the prediction was done on the waste collection amount. From the waste projection, it was determined that about 7 million tons of raw MSW will be available to deposit in landfill after completion of construction. This required amount of waste can be collected from the internal sources of Dhaka city as the waste collection prediction describes.

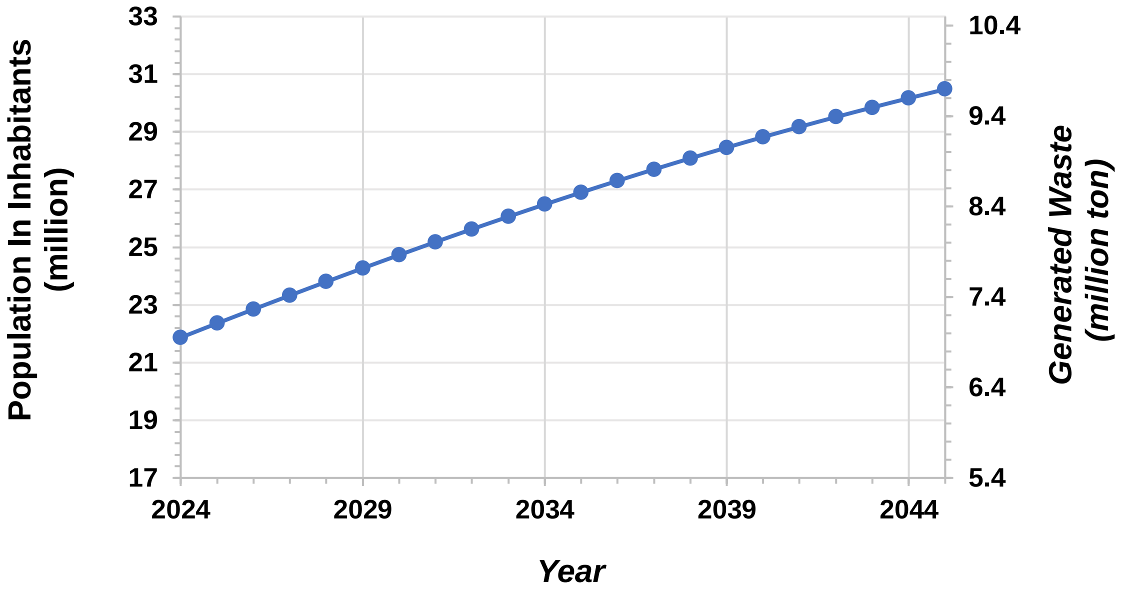

Fig. 4.13: Population and waste generation projection

From energetic calculation, in Fig. 4, it can be seen that energy potential of sewage treatment plant is 14 MW in 2025. Variation of potential throughout the economic life of the plant is insignificant. So a 14 MW generator is selected to operate during the 25 years operational time. On the other hand, the biogas generation from landfills keeps on increasing and power generation potential varies widely over the years. From 3 MW potential in 2025, it reaches 16 MW in 2044. Initially the λ parameter is less than one as the biogas generated from landfills is lower, but eventually it increases near the end of the economic lifetime.

4.7 Optimization of generator capacity to be installed for LFG plant

The power generation potential of a landfill site is not constant over the WTE power plant's lifetime. From Fig. 4.14 it is evident that generated power in a landfill reaches a peak value and then starts to decline. A typical WTE conversion power plant needs four years of construction period. After four years of the operational period, when the power generation potential of the landfill crosses 7500 KW, a 7.5 MW capacity generator will be installed. As a result the plant will produce power at full potential and there will be no loss in output. If no other generators are installed, there will be a substantial unutilized energy potential. In the year 2035 available power is more than 13 MW and in the final year of the economic life cycle, it again comes down to 13 MW as shown in Fig. 4.14. Thus harnessing a total of 13 MW power starting from the year 2035 is economically profitable. So another generator of 5.5 MW capacity will be operational from 2035. The combination of two generators will be able to produce 78% of the highest potential power in 2046.

Installing only one generator decreases initial cost. Total available power from the plant increases, reaches a peak point and then decreases with the increase of installed power as waste degradation occurs. As seen from Fig. 4.15, an installed power of 7.5 MW can produce maximum power during the lifetime of the plant. So, 7.5 MW installed power is adopted for scenarios with single generator.

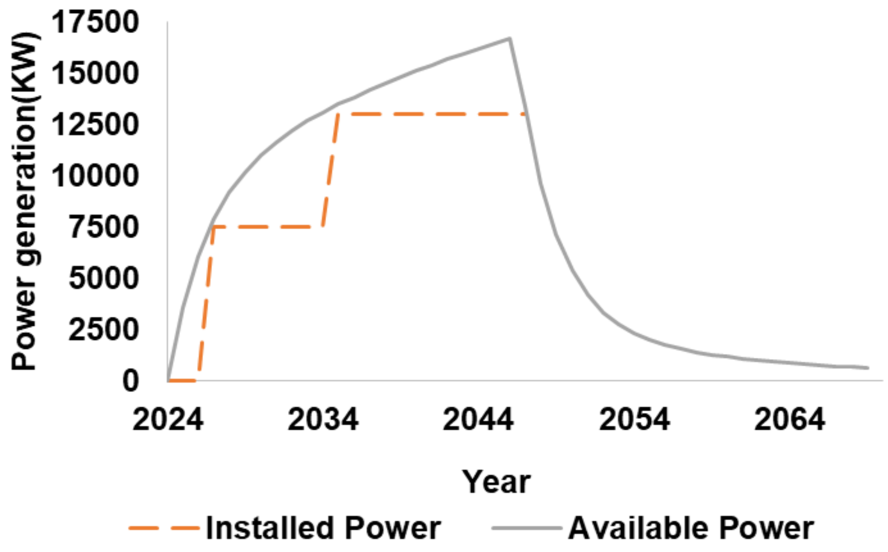

Fig. 4.14: Optimization of Capacity and Time of Installation of Generators.

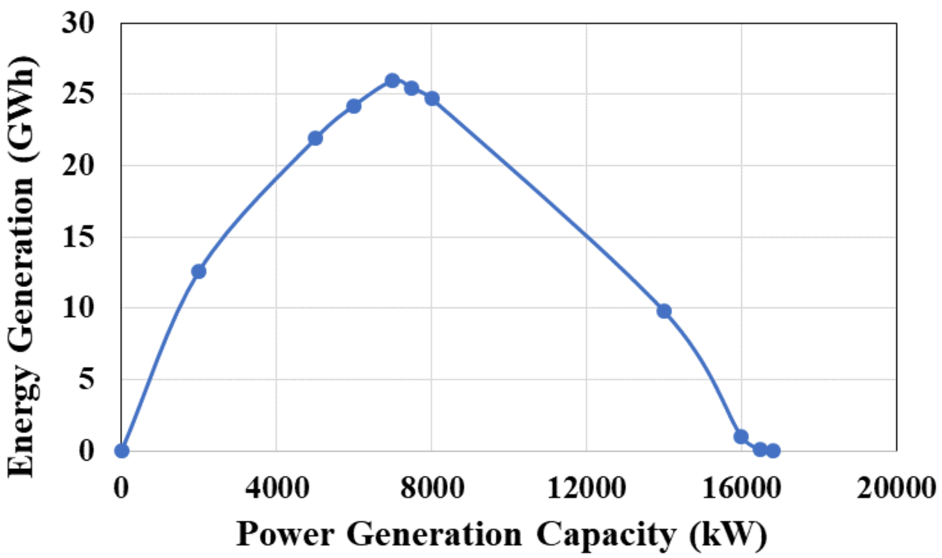

Fig. 4.15: Optimization of capacity while using single generator

4.8 Scenario analysis

After the calculation of available biogenic gas flow and maximum electricity generation potential using landfilling and sludge treatment procedures, we analyzed different scenarios considered above to determine the best possible condition to produce power. Maximum electricity generation potential was found to be 16651 kW and 19435 kW utilizing LFG and Biogas, respectively.

Scenario 1: Under this scenario, utilizing the biogas collected from the sludge treatment plant, 14000 kW electric power could be produced. This 14000 KW of minimum base power will be available throughout the sludge treatment plant's lifecycle.

Scenario 2: Under this scenario, the available LFG can produce 7000 kW between 2027 and 2045. Under this scenario, 61.32 GWhe electrical energy will be available annually, the maximum available energy per year from landfill when a single power generating unit is considered.

Scenario 3: For the escalation base model, the first generator group of 7500KW capacity will start power production in the year 2027, and the second generator group will produce power starting from the year 2035, totaling the power generation of 13000KW available from the year 2035. Both of the power generating units will produce power up to the year 2045.

Scenario 4: Under this combined LFG and biogas utilization scenario, the sewage treatment plant will produce minimum base power of 14000KW throughout its economic life cycle. The LFG based power generating unit will produce 7000 KW between 2027 and 2045. Totaling 21000KW power will be available between the year 2027 and 2045.

Scenario 5: In this combined LFG and biogas utilization scenario, an escalation-based power generating unit installation model was considered.

Scenario 6: In this scenario, thermal and electrical combined energy generation was considered. The maximum electricity generation is predicted as 236.52 GWhe and heat as 304.09 GWht under this scenario. Generated thermal energy would be enough to dry and remove 90% moisture content from the sludge resulting in 86% volume reduction of the residue generated in the sludge treatment plant.

Detailed energy and economic calculation for each case are presented in Table 4.2. It is seen that energy production is highest for scenarios 5 and 6, which is almost four times higher than scenario 2. The average per capita household electricity consumption in Bangladesh is 0.11 MWh/y [122]. Considering five household members, electricity produced in scenarios 5 and 6 can provide enough power for 420,000 residents and 2.1 million residencies which is around 10% of the population of Dhaka. On the other hand, the combined demand of industries around Dhaka city is 1289 MW [123]. Produced electricity can fulfill 47% of industrial demand. Scenarios 1,4 and 5 are economically viable as their NPV values are well above zero. Biogas from sewage treatment plant is considered in these cases which shares the prime portion of the power produced. Scenario 4 is most profitable indicated by its highest NPV. The result indicates the significance of optimizing the LFG plant's capacity to get the maximum energy generation and aiming for maximum energy potential results in a shorter availability period. Output of the sewage treatment plant varies a little over time. So no optimization was needed for this process. Internal rate of return of 9.69% is highest for scenario 1 which is above the considered interest rate.

Scenarios 5 and 6 require maximum installed capacity as they take into account biogas generated from both landfill and ST plants. SC6 uses recovered thermal energy for sludge drying. As a result, the initial investment is also higher for this case. It can also be observed from Table 4.2 that the LCOE value tends to decrease as the installed electrical power increases, i.e., price per unit of electricity can be lowered by installing a higher capacity plant. The LCOE value is maximum (110 USD/MWh) for scenario 3 and minimum (80 USD/MWh) for scenarios 1 and 4. In Bangladesh, the highest LCOE value of 157.8 USD/MWh and the lowest LCOE value of 119.9 USD/MWh can be seen for coal-based and nuclear-based power plants, respectively, for an operational period of 25 years [124]. So, it is evident that biogas usage will make the project economically viable even at a lower selling price than conventional energy sources.

Analysis of scenarios 3 and 4 shows that combining ST biogas with landfill gas for combustion increased energy potential by 50% along with an increase of 61.32 GWh/y electricity production. Moreover, from the economic perspective, the NPV value showed better results for scenario 4 although it has lowest LCOE value among all scenarios. Scenarios 4,5 and 6 which use biogas from both plants require much higher initial investment. But they have higher energy potential and cost per unit energy is also lowest for SC4 and SC5.

Reduction of emission is one of the vitally important aspects of waste to energy technology. The emissions avoided in the form of tons of CO_2 per year varies between 180 tCO_{2eq}/y and 693 tCO_{2eq}/y. It is seen that combined power plants provide maximum reduction of emissions along with the highest energy production. Per capita avoided emissions of 0.023 $kgCO_2$/inhab.y is 4.32% of the city's per capita CO_2 emissions as of 2045, considering average national emission of 0.533 tons per capita in Bangladesh [125].

Scenario 6 has several environmental benefits as it produces thermal energy along with electrical energy which is used for sludge drying. Drying of sludge generated from sewage treatment plant reduces levels of pathogenic viruses, helminth eggs and bacteria [126]. Furthermore, the amount of landfill area needed decreases due to the reduction of solid volume to be disposed. Though the NPV value is minimum amidst all the scenarios with some government incentives it is feasible to develop the project. For instance, it could be a small elevation in the energy tariff or a slight reduction of the interest rate. From sensitivity analysis it can be seen that for 0.01 USD/kWh increase in electricity price, increase rate of NPV value is highest for SC6. As the project can bring many environmental benefits for the entire city, it is profitable for the government even after some incentives.

Generated biogas can also be used in buses running through the cities. For highest power generating scenarios 5 and 6, generated biogas is around 0.33 million m^3/day up to year 2034 and 0.43 million m^3/day for rest of the years. The generated biogas can be supplied to around 5500 buses till year 2034 and 7000 buses for rest lifetime. Thus 1400-2700 t/y of NO_x generation can be avoided. NO_x can cause human respiratory illness. With the reduction of NO_x emission, air quality will be improved of the concerned city.

Table 4.3

Summary of the scenarios

Parameters	SC1	SC2	SC3	SC4	SC5	SC6
Electricity generation potential (MW)	14	7	13	21	27	27
Electricity produced in MWh/y	122,640	61,320	113,880	183,960	236,520	236,520
Avoided emissions (tCO_{2eq}/y)	359	180	334	539	693	693
NPV (million USD)	16.22	5.62	2.2	20.49	14.41	1.59
LCOE (USD/kWh)	0.08	0.09	0.11	0.08	0.09	0.10
PI	1.42	1.23	0.95	1.32	1.18	1.02
IRR (%)	9.69%	8.11	6.17	8.83	7.77	6.59
Initial investment (million USD)	38.19	24.08	43.76	63.91	81.95	93.44
Payback period (years)	9.71	11.92	15.13	10.70	12.22	13.4

The combined power plant brings the opportunity for development in the sanitary sector using energy approach. Successful implementation of the project could generate new waste treatment units which will eventually lead to environmental and social gain. Proper management of the project will generate environmental benefits decreasing greenhouse gas emissions and fossil fuel consumption as the collected biogas will be used for power generation. Besides, collection of biogas for power generation will reduce bad odors in the landfill region. Avoiding leachate leakage from landfills and the usage of sludge in the WWT plant will allow a better quality of groundwater. Consequently, proper drainage of wastewater will be achieved which will ensure better overall public health. The establishment of a biogas power plant will also create new green jobs. New jobs will be created for 1.04 to 5.04 persons per GWh per year, depending on the technology applied [127].

4.9 Sensitivity analysis

Sensitivity analysis was carried out to calculate the fluctuations of results with different parameters. SC4 shows higher NPV value in comparison to other scenarios. SC5 can produce more profit at selling price of 0.09 USD/kWh. But at present tariff rate SC4 is the most viable option. Again, SC4 is far better choice on the basis of carbon credit. SC3 and SC6 show negative values of NPV is most cases and may not be a profitable option. The sensitivity analysis indicates the significance of optimizing power generation from landfill as it seems more profitable than any other cases. Variations of NPV, Payback period, LCOE and PI were calculated with respect to changes in electricity price, WACC, initial cost and carbon credit for scenario 4, which uses biogas from both landfill and sewage treatment plant to generate electricity. It is seen that net present value decreases by almost 42% for a 1% increase of WACC from 7%. For further 1% increase it reduces by 62%, 145%, 281% respectively. NPV becomes negative and the project becomes unfeasible for a WACC value of 10% and more. But LCOE and payback period remain almost similar for 7-9% range. The sensitivity analysis indicates positive correlations of PI, NPV with changing electricity price, carbon credit and negative correlations with WACC and initial cost. The opposite scenario persists for the LCOE and the payback period. Net present value is most sensitive to the change in electricity price and least sensitive to the initial cost change. NPV becomes more than double for an increment of 0.01 USD/kWh of electricity price. The result also shows that WACC has no effect on the payback period and little fluctuations with carbon credit and initial cost. But electricity selling price can reduce it by one year with 0.01 USD/kWh change from 0.07 USD/kWh. Only WACC affects the LCOE but it indicates that the project is unprofitable at the present tariff rate. The variation of PI value is maximum with a change in electricity price and minimum for change in the initial cost. PI is always more than one for variations in selling price, initial cost and carbon credit. But it is greater than one, i.e., the project is profitable for 7-9% range of WACC. Therefore, variation in WACC value is the most significant among the different parameters.

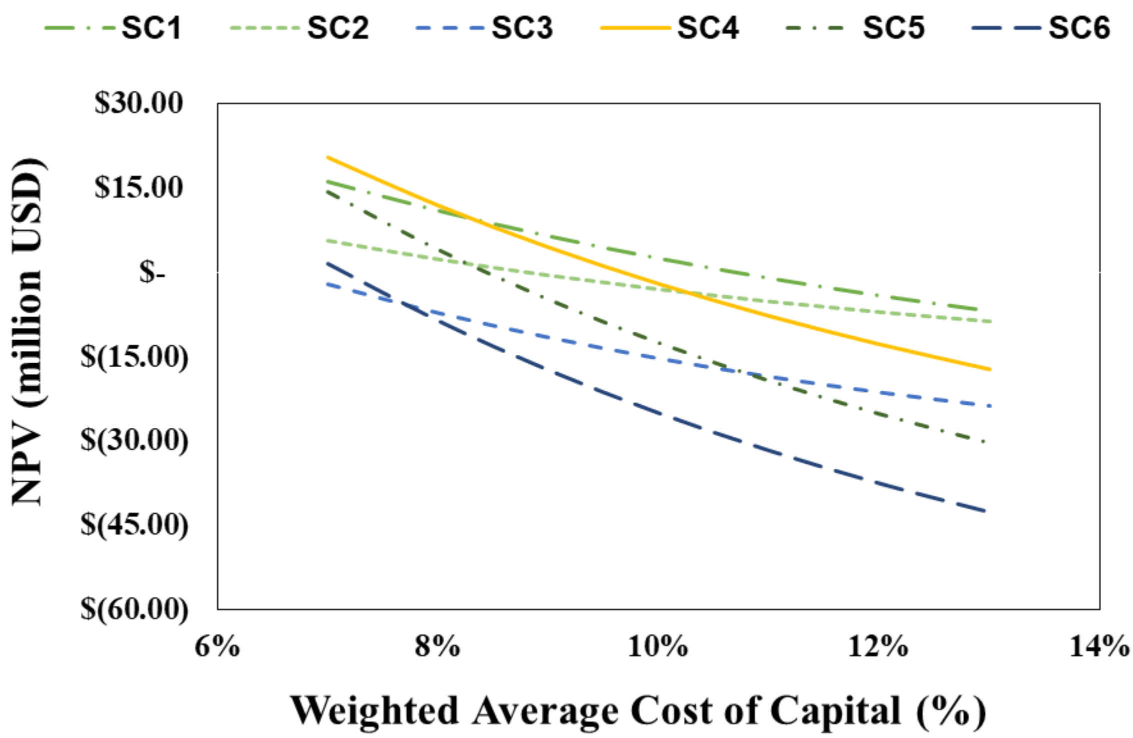

Fig. 4.16: Sensitivity analysis of NPV versus WACC

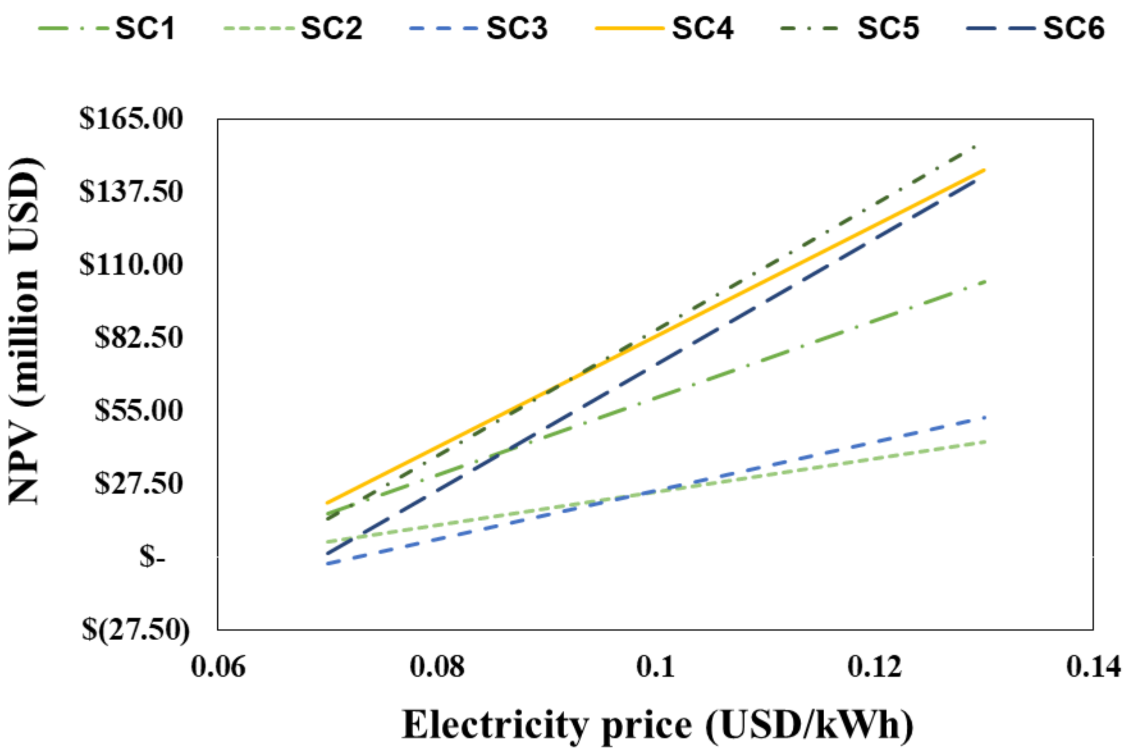

Fig. 4.17: Sensitivity analysis of NPV versus electricity price

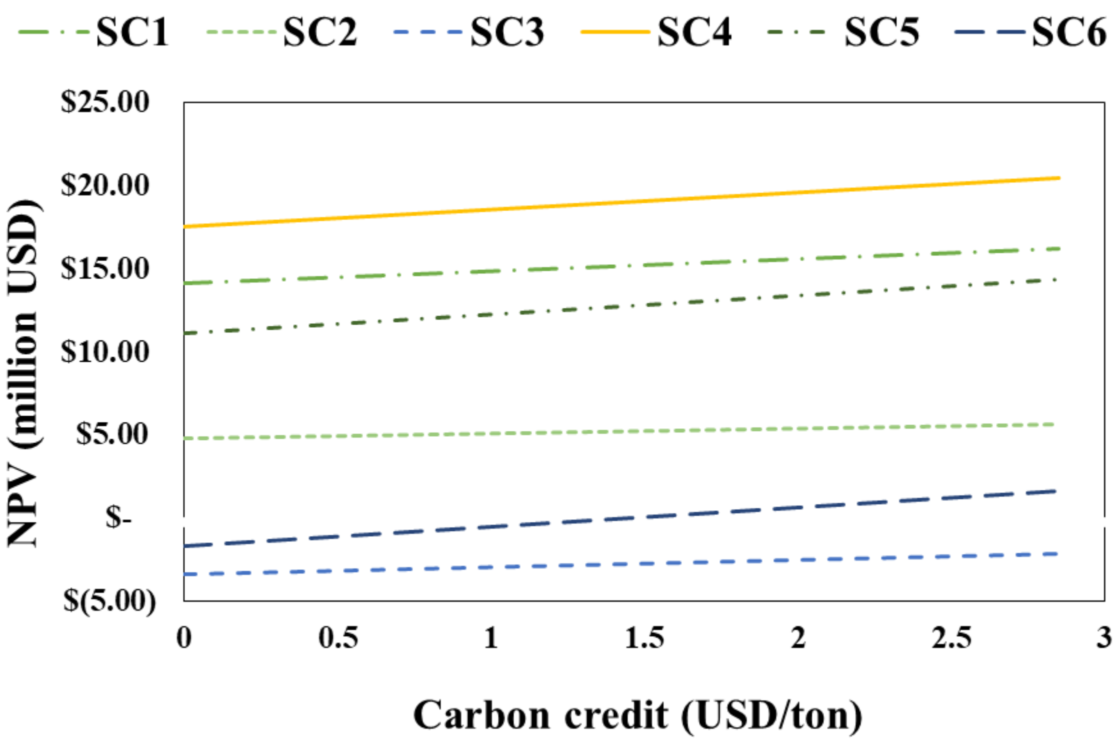

Fig. 4.18: Sensitivity analysis of NPV versus carbon credit

Chapter 5: Discussion

Part-I

The technical and financial feasibility and environmental impact of a 10 MW biomass-based power plant are assessed in this research. This research's significance is to compensate for the significant study gap regarding the MSW management studies in Dhaka city to some extent. The technical assessment provides the energy potential of Dhaka city’s MSW, whereas the financial evaluation provides a cost estimation of establishing the plant by evaluating the financial indicators. The sensitivity analysis illustrates the impact of input parameters on the financial model, enabling the decision-makers to identify the most impactful input parameters and their impact extent. The environmental assessment provides an emission reduction potential of this incineration WTE conversion technology.

The results show that the incineration WTE conversion technology presents a unique possibility from Dhaka city's perspective to address MSW management. However, the economic analysis indicates that the financial feasibility of establishing an incineration WTE conversion plant is low as the required LCOE per KWh is higher than the current electricity tariff rate. Although, the other financial indicator indicates the feasibility of this plant. But the decision-makers may prefer to integrate incineration WTE conversion technology in the existing waste management system in Dhaka city as it has a higher waste handling capacity and can reduce the volume of the waste up to 80%, thus reducing the landfilling area requirement, which is more significant from the perspective of Dhaka city. Besides, it can present an environmental significance by reducing greenhouse emissions from the existing landfills. So, this research promotes the establishment of an incineration WTE conversion plant to reduce the carbon footprint and compensate for the global climate.

Similar techno-economic and environmental impact analysis on the conventional WTE technologies, i.e., Anaerobic digestion, sanitary landfilling with Methane extraction, are suggested for future research. This research assumes that the incineration WTE conversion plant is state-owned. Other researchers may study the financial feasibility of private investment in incineration WTE conversion technology, applying the same models used in this research.

Part-II

Dhaka is a densely populated city that faces persistent problems in waste management. MSW and sludge are dumped in landfills and water bodies which pollute the land area and rivers. This paper demonstrates the biogas' energy potential harnessed from landfills and sewage systems, their emission reduction capacity and economic analysis. Stepped method was used to attain the optimum capacity and time of installation of generators. It is found that installing a 7.5 MW generator after four years and another 5.5 MW generator after twelve years provides maximum power. Several scenarios were studied to compare and find out the best one. The combined use of biogas from landfill and sewage treatment plant shows the most reasonable result with a power generating capacity of 21 MW and a payback period of 10.70 years.

Energy production around the world is primarily dependent on conventional energy sources. Researches are trying to shift the energy balance to renewable sources. WTE technologies provide scopes to use wastes as fuel. It decreases the burden on conventional sources along with reducing waste management problems. WTE technologies are widely used in developed countries but are still not well established in developing countries due to lack of proper planning, infrastructure and research. The methodology presented in the study can be followed to study the energy potential of landfill biogas for other Asian countries.

The energy and economic analysis will enable policymakers to consider WTE technology as waste management and power generation option for a populated city like Dhaka. The project will bring economic benefits in addition to improvements in the sanitary system. It will eventually develop average public health and decrease investments in the health sector.

The study considered IPCC model to predict biogas generated from landfill. Use of other models such as- LandGEM, TNO-model, Afvalzorg, to find the same together with more decision-making scenarios is suggested for future studies.

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