Anaerobic Digestion of Municipal Solid Waste of Islamabad – a Techno-economic Feasibility Analysis

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ABSTRACT

Renewable energy seems to be the only way towards a sustainable future and solves two major global issues, especially, for the developing countries that are: depletion of fossil fuels due to overuse and abrupt climate change. Pakistan is facing severe energy crisis these days as energy prices are increasing day by day and almost 27% of its population has no access to electricity. Another important problem faced by Pakistan is solid waste management. Proper disposal of solid waste remains a challenge in both urban and rural areas of Pakistan as it is either openly burned or dumped in low lying areas. The alarming increase in population growth and increased economic activity has a negative impact on both energy availability and solid waste management. Energy from biomass is a promising solution to both of these issues and is gaining popularity due to its effectiveness. Municipal Solid Waste of Pakistan has very high potential of producing biomass energy as its major constituent is organic material. The purpose of this research is to analyze the potential of biomass energy from municipal solid waste in Islamabad. This paper compares two waste to energy technologies i.e., Landfill Gas and Anaerobic Digestion and provides a complete techno economic feasibility analysis of both technologies. The results of this research indicate that over the lifetime of 20 years the methane yield for AD and LFG is estimated to be about (126.6.6 to 286.1) x10^6 m^3 */ year* and (1.6 to 39.7) x10^6 m^3 */ year*, respectively. The electricity generation potential of the two technologies ranged between for AD (400.3 to 904.8) *GWh / year* and (3.5 to 84.8) *GWh / year* for LFG implantation. The Levelized Cost of Energy for digester plant ranges between (0.0312 to 0.0131) *USD / kWh* while for the LFG plant it lies between (0.0886 to 0.0285) *USD / kWh*. The Total Life Cycle Cost of AD and LFG plants is estimated to be 208 million USD and 38 million USD.

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Abbreviations

AD	Anaerobic Digestion
GHG	Greenhouse Gases
GWP	Global Warming Potential
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LFG	Landfill Gas
MSW	Municipal Solid Waste
NPV	Net Present Value
O&M	Operation and Maintenance
PBP	Payback Period
TLCC	Total Life Cycle Cost

Chapter 1

1 Introduction

The long-term use of non-renewable energy sources like fossil fuels have resulted into global warming as the emissions of greenhouse gases (GHGs) have huge adverse effects on the human health and the environment. Lately, non-renewable energy sources have been considered as a major threat to the global environment and, therefore, several industries and transportations are being shifted towards the renewable energy sources, worldwide. Among many clean energy sources like Solar, Wind and Hydrothermal, waste-to-energy has gained much attention as this type of renewable energy source offers dual benefit by not only resolving the issues of energy crisis but also providing a promising solution for solid waste management which is yet another big concern in the near future. The reason being that, in 2016, the mismanagement of solid waste of 1.6 billion tonnes made contributed 5% to the global emissions according to World Bank report (Kaza, 2018).

Pakistan has been facing both the problems of energy crisis as well as poor management of solid waste and with population and economy on the rise, this has always remained a serious concern for the governing bodies. The population is expected to reach 363 million by 2050 (Korai, 2017) which means a greater energy demand and waste production. The capital city of Pakistan, Islamabad, is facing these challenges as its population growth rate was recorded as 4.91% by Pakistan Bureau of Statistics in 2017. The generated waste is either openly dumped or burned which means the city does not take any advantage from this source of energy which is being wasted and the issue is addressed in this study by providing assessment of bioenergy recovery technologies as they can contribute towards reduction in 70% of the energy made from imported fuels in Pakistan. So waste-to-energy recovery technologies like anaerobic digestion (AD) and landfill gas (LFG) for municipal solid waste (MSW) giving energy in the form of power and gas which is sustainable, harmless to the environment and economically reasonable. In AD technology, biogas is produced in form of methane CH_4 in 55-75% by volume and other main greenhouse gas is CO_2 which is 25-45% by volume of total gas is produced and other is non-methane organic carbon and H_2S etc. For landfill, methane volume is 50-55% of its total volume of gas produced.

As total gas is mixture of different gases so we need to remove all gases other than methane and this is done by using absorber to extract remaining gases. This process is upgradation of natural gas and this upgradation use as fuel in combustion engine. As discussed, the two technologies, anaerobic digestion (AD) and landfill gas (LFG), will be studied for their potential of implantation in Islamabad. Anaerobic digester is a controlled environment container in which organic fraction of MSW is degraded and is usually for has a concrete, metal or plastic structure. The input in AD is organic fraction of MSW and it is consisting of four steps with very first of pretreatment of waste and this is done through formation of homogeneous mixture of input feedstock. Second is digestion of waste and third is recovery of the gas followed by final step of treatment of residue that is known as digestate. Digester is selected by on feedstock which is either dry or wet and input will be continuous or batch system and temperature at which operation is done either thermophilic or mesophilic and done on single stage or multi stage.

In landfill the biogas also produced but methane concentration is less and also collection of bio gas is also less with largely losses is done. Also need large are as compare to AD and less expensive. Main problem is to formation of leachate which will be contaminating ground water and production of gas take more time as compare to AD.

1.1 Municipal Solid Waste

Other name of municipal solid waste (MSW) is trash or garbage which means the same as disposing of the materials in metropolitan territories, which include mainly of household materials and sometime include the commercial waste, institutional waste and industry waste which is collected by the waste collecting corporation of the city. Food waste, paper, wood decoration, cotton, and calfskin, are typical compositions in MSW which may be source of bioenergy. Other waste includes demolish waste, construction waste and agricultural waste which is also called industrial waste. Materials for non-renewable energy sources are plastics, textures which are likewise found in MSW.

1.2 Municipal Solid Waste Situation in Pakistan

As a result of population increase and economic development, the solid waste management has transformed into an extreme issue for almost all the regions. The hazardous gases are released from the solid waste resulting in bad odor, air emissions especially particulate matter which is very dangerous for the human health. In order to cater all above problems brilliant and smart waste management system is required. Pakistan is sixth largest country in the world on the basis of population and its population is increasing very drastically. Pakistan’s population for 2020 is estimated to be 223,096,192. This increase in population results in more solid waste generation and the energy demand also increases with the increase in population.

If solid waste is not properly managed then it will cause huge problem. So, solution of this problem is to generate electricity from the MSW. By adopting waste to energy technology we will be able to lessen the volume of the waste and fulfil the energy demand. In developing countries Municipal Solid Waste generation rate increases very fast. Pakistan waste generation rate increase by 2.4% annually. In Pakistan approximately 20 million tons of the waste is produced yearly. Karachi which is the largest city of Pakistan, produces almost 9,000 tons of municipal solid waste daily. In Lahore the second biggest city of Pakistan, there is only one control disposal site and no formal recycling framework exists. Other cities like Islamabad or Peshawar also generate large amount of solid waste and it is a big challenge to manage this waste. The root factors for the stinging trash issue in Pakistan are absence of metropolitan planning, absence of public awareness and lack of proper infrastructure. The quantity of solid waste produced every day depends on the income and is approximately 0.3 to 0.6 kg per capita per day. The generated waste is sent to the dumping site without considering of recycling the useful waste. However, scavengers regularly visit the dumping site and collect the useful materials like metal, glass etc. which they sell to the scrap shop. 90% of waste volume can be reduced by adopting waste to energy techniques but unfortunately in Pakistan these practices are not common at all. By open dumping of waste methane produced from organic component of Municipal Solid Waste is directly released into the environment.

(a)

(b)

(c) *(d)*

Figure 1.1: (a) Scavengers collecting the recyclables, (b) Lakhodair landfill site Lahore, Dumping site I-12 Islamabad, (d) Dumping site Karachi

1.3 Electricity Demand

As for electricity, it is a necessity of life and country growth. On 30th June, 2020 installed power generation capacity of electricity is noted as 38,719 MW and which is previously noted as 38,995 MW on 30th June, 2019 where the difference is due to net decrease in power 276 MW. In public sector electricity generation was 19,621 MW, whereas, in private sector electricity generation capacity was 19,098 MW and also include KE as private sector (NEPRA, 2020).

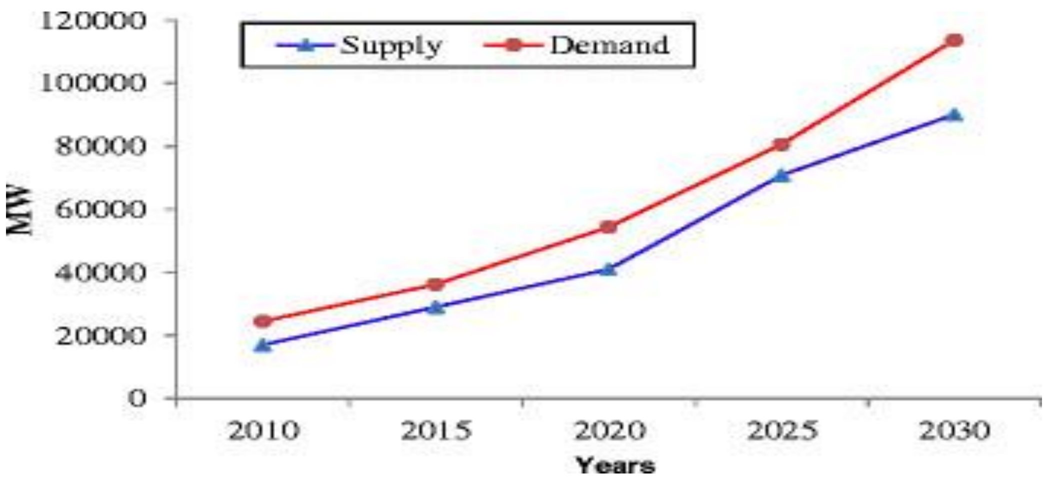


Figure 1.2: Expected electricity supply and demand

1.4 Islamabad Situation

Islamabad is the capital of Pakistan, and this is one of the planned cities in Pakistan but the implementation of projects is not properly done. The city is always challenged by problems related to improper development, traffic congestion, different environmental issues like water supply and sanitation and the other major environmental issue is related to improper disposal of municipal solid waste. Although CDA is responsible for the well-being of public health but minimal measures have been taken in this regard as not only there is an absence of proper disposal site for waste but also many dumping sites are located near residential areas causing serious odor problems. Population of Islamabad is approximately 2,316,890 in 2020 with average waste generation rate of 0.6 kg per capita per day leading to the total waste production of 507,399 tons with collection efficiency is 90 percent. The current dump site is I-12 with not much recycling and. The high organic fraction of 57% in waste makes it highly suitable for generating bioenergy.

1.5 Problem Statement

The municipal solid waste of Islamabad is a potential resource of renewable energy, which is currently being wasted and causing environmental damage.

- In this project, a detailed study will be performed in order to evaluate the feasibility of two Waste to Energy technologies: Anaerobic Digestion and Landfill Gas to Energy Recovery.

- The data and information are collected and gathered based on an extensive review of local and international published researches, conducted by well reputable, government entities and individual experts.

1.6 Objectives

- Conducting techno-economic feasibility analysis of Anaerobic Digestion (AD) and Landfill gas to Energy (LFGTE) recovery from Municipal Solid Waste of Islamabad.

- Environmental benefits offered by using each technology for Organic fraction of Municipal Solid Waste of Islamabad.

1.7 Innovation

Previously studies have been conducted on design or catered one or two parameters, but our study provides design parameters and comparison of two waste to energy technologies along with economic parameters. For this purpose, we aim to conduct a detailed study analyzing technical, economic and environmental feasibility. Such studies are being conducted all over the world but still not for Islamabad which lead to innovation.

Chapter 2

2 Literature Review

2.1 Techno-Economic feasibility assessment of landfill gas (LFG) and anaerobic digestion (AD) in China

The study was carried out by Dan Cudjoe, Myat Su Han, Aditya P. Nandiwardhana in the year 2020.

This study evaluated that the biogas generated from the municipal solid waste collected for the disposal in provinces of china (2004 to 2018) by using two technologies which are anaerobic digestion and other is landfill gas. By utilization of the methods which are Net Present Value (NPV) and Levelized Cost of Energy (LCOE) to find out the techno-economic feasibility of landfill gas and other is anaerobic digestion. It was found that the technology related to anaerobic digestion (AD) generate high amount of energy as compare to landfill gas (LFG) related technology. Both landfill gas (LFG) and anaerobic digestion in China feasible but anaerobic digestion (AD) give net present value was more as compare landfill gas (LFG) because high production of biogas. Also, this study showed that if energy is not recovered from landfill, then cause of global warming and recovery would be done then 71.5% reduced the potential of GHG, on the other hand anaerobic digestion (AD) technology reduced 92.7% potential of GHG. Anaerobic Digestion (AD) technology had potential to generate electricity from 636.67 to 33610.22 GWh. So, this study provides the scientific evidence to invest in anaerobic digestion is more beneficial in provinces of china.

2.2 A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia

The study was carried out by Laith A. Hadidi, Mohamed Mahmoud Omer in the year 2017.

The finding of this study is that the energy demand in Saudi Arabia increase very rapidly this is due to movement of population towards the urban area and also population increase at fast rate due to increase in population municipal solid waste also increase. Only solution to manage the waste and fulfil the energy demand they should be introduced waste to energy technology. This paper breaks down the current circumstance of municipal solid waste the board in Saudi Arabia and techniques economic model to evaluate the suitability of waste to energy in Saudi Arabia and find out waste management difficulties and satisfy its anticipated energy demand. The examination fosters a financial Some indicators to find the feasibility of technologies according to economic perspective model to research the feasibility of waste to energy generation plants using gasification and Anaerobic Digestion. like internal rate of return (IRR), net present value (NPV), Levelized Cost of Waste (LCOW) payback period, Levelized Cost of Electricity (LCOE) and discounted payback period etc. to found the cost estimation for waste to energy model and study evaluated that some factor i.e., capacity factor and facility waste capacity affecting financial model for two technologies of gasification and Anaerobic Digestion.

2.3 Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria

The study was carried out by T.R. Ayodele, A.S.O. Ogunjuyigbe, M.A. Alao in the year 2018

In this paper evaluated environmental and economical assessment from biogas generated electricity from the organic fraction of municipal solid waste by using two technologies which are anaerobic digestion (AD) and other is landfill gas (LFG) for the city of Ibadan, Nigeria. Environmental assessment is evaluated from some indicators life cycle assessment technique and economic viability is determined by tools like internal rate of return (IRR), net present value (NPV), payback period and Levelized Cost of Electricity (LCOE). sensitivity analysis is done to find out the effect on economic viability of two technologies of anaerobic digestion (AD) and other is landfill gas (LFG) by capacity factor, waste collection rate and per capita waste generation rate. The recovery of methane is higher in of anaerobic digestion (AD) which is (104.66-212.15) million m^3/year with electricity generation potential 321.73 to 652.15 GWh and other is landfill gas (LFG) is about (22.65-127.65) million m^3/year with electricity generation potential 63.25 to 436.18 GWh. As finding show positive net present value so it is economical viable for both of anaerobic digestion (AD) and other is landfill gas (LFG) technologies. This study provides the evidence to invest in anaerobic digestion is more beneficial in Ibadan, Nigeria.

2.4 The feasibility of municipal solid waste for energy generation and its existing management practices in Pakistan

The study was carried out by Muhammad Safar Korai, Rasool Bux Mahar, Muhammad Aslam Uqaili in the year 2017

This study has been acted to evaluate its current energy generation management and to assess the Viability of energy generation through municipal solid waste in Pakistan. From this study we found that management of municipal solid waste throughout the Pakistan is not proper practice to manage it in fact the waste is dump openly and has not a proper disposal site for municipal solid waste. But if we are generated the electricity from this waste either thermally or biologically then we generate lot of electricity. About 70% of energy that is imported can be reduced if biologically generation of energy from the solid waste but we are wasted formation of this kind of renewable energy. The findings of this paper tell us if we want sustainable development and have healthy economic growth then waste to energy is best option for this.

Chapter 3

3 Methodology

3.1 Waste Generation

One of the most important factors for determination of waste to energy potential is the quantity of waste that is being generated. The amount of waste generated is directly influenced by the population and economy of the area. The economy improves as a result of increase in population which leads to increased generation rate of MSW. We need to consider the amount of waste generated over a period of 20 years. The total amount of waste generated (in *tons/year*) over a given (*t*) can be calculated by using the following formula:

$$MW_G(t) = \frac{Pop(t)\ \times\ W_{GR}(t)\ \ \times 365}{1000}(ton/year) \tag{1}$$

In this equation MW_G (*t*) is the projected total waste generation (*tons/year*), Pop (*t*) is the population projection estimated over a period of time (*t*) and W_{GR} (*t*) is the per capita waste generation rate for that period of time. The waste generation rate is measured in *kg/person/day*.

The following equations are used to calculate waste generation rate and estimated population projection:

$$Pop\ (t) =\ Pop_{base}\ \times\ (1 +\ r_{pop})^t \tag{2}$$

Here Pop_{base} is the initial population and r_{pop} is the population growth rate.

$$W_{GR}\ (t) =\ W_{GR_{base}} +\ q \tag{3}$$

Here W_{GR} (*t*) is the initial waste generation rate and q is the waste generation rate increase each year.

Table 3.1: Parameters for evaluating waste generation potential for city of Islamabad

Parameters	Pop_{base}	r_{pop}	$W_{GR(base)}$	q	Lifetime (*t*)
Value	2316890	4.91%	0.6 *kg/capita/day*	0.0105 *kg/capita/day*	20 *years*

Sources: 1. Kazi et al,2018 2. PBS, 2017

3.2 Waste Collection

Waste collection rate is a very important factor in determining the total amount of waste available for waste to energy transformation and it varies for countries as well as cities. As Islamabad is the capital of Pakistan and its waste collection system is very efficient, the current waste collection rate for the city is very high. Despite having a very high waste collection rate not all the wastes generated are collected and dumped. It is difficult to reach the wastes that are deposited in far off and unauthorized places. Thus, we use the following formula to calculate the total amount of waste collected:

$$MW_F\ (tons/year) = C_r \times MW_G(t) \tag{4}$$

Here, MW_G (*t*) is the total amount of the waste generated per year which we calculated from equation 1, and C_r is the waste collection rate for the city of Islamabad. The waste calculation rate for Islamabad is 91% (Raheem et al., 2016). Sixty percent of this waste is collected by CDA and the rest is contracted out to private contractors (Zia et al., 2017)

3.3 Waste Composition

The composition of waste varies from location to location on the basis of various factors. These factors include economy, population, culture and season of the area. The composition of MSW determines its waste to energy potential and also helps in deciding the type of technology used for energy production. The main component of MSW of Islamabad is organic which means it has high moisture content and degradation rate, this makes it highly suitable for Anaerobic Digestion. In case of landfill to energy technology recyclable material is removed from the collected waste and the rest of waste is landfilled. The total amount of organic fraction available for Anaerobic Digestion is calculated by using the following formula:

$$MW_{OF}(t) = MW_F\ (t) \times f \tag{5}$$

Here MW_F (*t*) is the total amount of waste collected in *tons / year* and f is the percentage of organic fraction present in that waste. the MSW of Islamabad consists of 57% of Organic Fraction (Zia et al., 2017)

The values for proximate and ultimate analysis for MSW of different cities of Pakistan are taken from literature and recorded in Table no.

Table 3.2: Characterization using proximate and ultimate analysis

City	Proximate analysis				Ultimate analysis					
	MC (%)	TS (%)	VM (%)	FC (%)	C (%)	H (%)	N (%)	S (%)	O (%)	C/N
Islamabad	58.20	41.81	15.43	11.32	41.64	6.53	1.07	0.13	39.79	39
Rawalpindi	24.81	75.19	18.04	7.09	44.78	6.32	0.80	0.11	31.86	56
Lahore	56.04	43.96	21.54	13.54	39.11	5.49	0.68	0.13	40.46	57
Average	46.35	53.65	18.34	10.65	41.84	6.11	0.85	0.12	31.37	51

Source: Korai et al., 2017

3.4 Determination of Methane Yield

3.4.1 Methane Generation from Anaerobic Digestion Technology

The energy potential of the waste that is fed into the digester depends on the amount of biogas (*m^3 / ton*) produced from the waste. The theoretical value of the amount of biogas generated from the substrate is calculated by using the Bushwell's equation (Nielfa et al., 2015). The values for elemental analysis (table) of the waste material are used in this equation which is based on the stoichiometry of degradation of waste.

$$C_wH_aO_bN_c + \left(w - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right) H_2O \rightarrow \left(\frac{w}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) CO_2 + \left(\frac{w}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) \quad (6)$$

The constants w, a, b and c in the equation are the normalized mole ratios (Salami et al., 2011) and are obtained as follows:

$$w = \frac{K(C)}{M(C)} \quad (7)$$

$$a = \frac{K(H)}{M(H)} \tag{8}$$

$$b = \frac{K(O)}{M(O)} \tag{9}$$

$$c = \frac{K(N)}{M(N)} \tag{10}$$

Here K is the elemental composition of carbon, oxygen nitrogen and hydrogen(table) and M is the molar mass of those elements (table).

Table 3.3: Molar mass of the elements

Element	Carbon (C)	Hydrogen (H)	Oxygen (O)	Nitrogen (N)
Molar mass	12.01	1.01	16.0	14.01

The specific theoretical methane yield is measured at standard temperature (0˚C) and pressure (1 atm) and its unit is *Nm^3CH_4 / ton*. It is calculated by using the following equation (Nielfa et al., 2015):

$$S_{CH_4} = 22400 \times \left(\frac{\frac{w}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}}{12w + a + 16b + 14c} \right) \tag{11}$$

The actual amount of biogas produced from waste degradation is less than the theoretical methane yield. This is because only 85% of the organic fraction is used for methane generation and the remaining 5% is either utilized for cell synthesis of microorganisms or it is not degraded in the anaerobic digester. The actual methane yield (*m^3 / year*) for anaerobic digestion is estimated by using the following formula:

$$CH_4 = MW_{OF} \times S_{CH_4} \times F_C \tag{12}$$

Here F_c is the fraction of organic matter that is utilized for the production of methane gas by its degradation through microorganisms. The value of F_c is taken as 85%.

3.4.2 Methane Yield from Landfill

The landfill that we are considering in this research is a conventional landfill and its biogas generation capability is obtained using a model called Landfill Generation Emission (LandGem software 3.02). the methane generation potential for landfill is measured in *m^3/year*. This model is based on first order decomposition and it was developed by US Environmental Protection Agency (US EPA, 2005). The model is given as:

$$CH_{4(LFG)} = \sum_{i=1}^{y} KL_O \left(\frac{MW_{LF}}{10}\right) e^{-kt_{ij}} \qquad (13)$$

Here i is the 1-year increment, j is the 0.1-year time increment, y is the initial year of waste acceptance, k is the methane generation rate (*per year*), L_o is the potential methane generation capacity (*m^3 / ton*), MW_{LF} is the amount of waste that is landfilled annually (*tons/ year)* and t_{ij} is the age of jth section of waste in the year i. (Ayodele et al, 2018**).**

The amount of waste generated over the lifetime of Landfill MW_{LF} (*tons / year*) is entered in the software which then gives you the estimated amount of methane gas generated (*m^3 / year*) over the lifetime of the Landfill. The value for methane generation potential differs moisture content, waste degradation rate and climate of the area.

Table 3.4: Parameters for calculation of Landfill methane generation potential

Parameter	Methane generation, k (year$^{-1)}$	Potential methane generation capacity (m^3 / ton)
Value	0.4	100

3.5 Electricity Generation Potential

3.5.1 Electricity Potential of Anaerobic Digestion Technology

The amount of estimated electrical energy that can be produced from Anaerobic Digestion technology depends on various factors such as working capacity of the plant and can be calculated by using the following formula:

$$Ep_{AD} = \frac{CH_{4(AD)} \times Eff \times LHV_{CH_4} \times CF}{3.6} \tag{14}$$

Here, Eff is the electricity generation efficiency of the electricity generator, $CH_{4(AD)}$ is the actual volume of methane generated from the Anaerobic Digestion plant, CF is the capacity factor which is the ratio between the amount of waste (*tons*) processed during the year to the actual amount of waste that could be processed if the plant were to be operated throughout the year that means at its maximum capacity and LHV_{CH4} is the lower heating value of methane gas.

3.5.2 Electricity Potential of Landfill Technology

The electricity generation potential for Landfill gas to energy technology can be determined by using the following equation:

$$Ep_{LFG} = \frac{CH_{4(LFG)} \times Eff \times \lambda \times (1 - f_{ox}) \times CF}{3.6} \tag{15}$$

Here, $CH_{4(LFG)}$ is the volume of methane gas generated from the Landfill, Eff is the efficiency of electricity generator, λ is the methane collection efficiency, f_{ox} is the oxidation factor in the Landfill and CF is the capacity factor of plant.

Table 3.5: Parameters for electricity potential calculation for AD and LFG

Parameter	Eff (%)	CF (%)	LHV_{CH4} (*MJ / m*^{3})	Λ (%)	F_{ox} (%)
Value	36	85	37.2	75	10

Source: Ayodele et al, 2018

3.6 Plant Size

3.6.1 Plant Size for Anaerobic Digestion

The size of the Anaerobic Digestion plant is taken in *MW* and it is based on the assumption that the plant stays functional throughout the year (i.e.8760 hours), this is because in an ideal scenario electricity is supposed to be generated throughout the year without any break. The equation used to calculate the plant size for Anaerobic Digestion is as follows:

$$Ps_{AD} = \frac{Ep_{AD}}{8760} \tag{16}$$

3.6.2 Plant Size for Landfill Gas to Energy Plant

The installed capacity (plant size) for Landfill gas to energy plant is determined by using the given equation:

$$Ps_{LFG} = \frac{Ep_{LFG}}{8760} \tag{17}$$

3.7 Investment and O&M Cost

3.7.1 Investment and O&M Cost for Anaerobic Digestion

The formula used for the calculation of investment cost for Anaerobic Digestion technology is given below:

$$C_{inv(AD)}(USD) = C_{avg}\left(\frac{USD}{kWh}\right) \times P_{s(AD)}(kWh) \tag{18}$$

Here P_s is the plant size for Anaerobic Digestion and C_{avg} is the global weighted average capital cost of AD plant. The value of C_{avg} is taken as 2141 *USD / kWh* (IRENA, 2020)

The Operation & Maintenance cost of an Anaerobic Digestion plant is divided into fixed (F_{OM}) and variable (V_{OM}) Operation & Maintenance cost. Fixed Operation & Maintenance cost mainly consists of insurance, labor costs, routine maintenance and parts replacement. On the other hand, the variable Operation & Maintenance cost includes unexpected maintenance, fuel costs, waste disposal and unscheduled machinery replacement. The equation used for the calculation of O&M cost of Anaerobic Digestion plant is given below (Cudjoe et al,2020):

$$C_{OM(AD)} = 0.06C_{inv} + 0.005E_p \tag{19}$$

Here F_{om} costs are taken as 6% (IRENA 2020) of the investment cost and V_{om} is taken as 0.5% (Hadidi and Omer, 2017) of the electricity generation potential of plant.

3.7.2 Investment and O&M Cost for LFG to Energy Technology

The investment cost for Landfill Gas to energy plant is determined by using the equation given below:

$$C_{inv(LFG)} = \sum_{k=1}^{5} C_k \tag{20}$$

The total investment cost consists of installed capital cost of vertical gas extraction wells (C_1), the cost of installing pipes and wellheads (C_2), the knockout, blower and flare system installing cost (C_3), engineering and surveying cost (C_4) and the cost of Landfill Gas technology plant installation (C_5).

The equations for calculation of these individual costs are as follows:

$$C_1 = [S(ft) - 10(ft)] \times 85USD \times N \tag{21}$$

$$C_2 = 17000USD \times N \tag{22}$$

$$C_3 = \left(CH_{4(LFG)}\right)^{0.6} \times 4600USD \tag{23}$$

$$C_4 = 700\,USD\ \times N \tag{24}$$

$$C_5 = \left(1300USD \times P_{s(LFG)}\right) + 1100000USD \tag{25}$$

Here, S is the depth of the well and N is the total number of wells that are dug at the landfill site. The value of S is taken as 50*m* and the value of N is taken as 114.

The Operation & Maintenance cost for Landfill technology mainly consists of two types of costs, O&M cost for the landfill site and O&M for the landfill plant and is calculated by using the following formulas:

$$C_{\mathrm{O\&M(LFG)}} = C_{\mathrm{O\&M(plant)}} + C_{\mathrm{O\&M(site)}} \tag{26}$$

$$C_{\mathrm{O\&M(plant)}} = 0.025USD \times E_{p(LFG)} \tag{27}$$

$$C_{\mathrm{O\&M(site)}} = 2600USD \times N + 5100USD \tag{28}$$

3.8 Calculation of Area Cost

3.8.1 Area Cost for Anaerobic Digestion Plant

The land area required for installing a digester of 1000 *tons / year* waste capacity is almost 0.1 *acre.* As total amount of MSW available for Anaerobic Digestion is 263,188 *tons / year*, a land area of 26 *acres* will be required for the Anaerobic Digestion plant.

The MSW of Islamabad is currently being dumped in the I-12 dumpsite. Some other locations such as Kuri and Sangjani are also being considered but currently no better option other than I-12 is available for this purpose. The cost of 1 sq-yard in I-12 is Rs 18000/- (FBR, 2019). This makes the total cost required for for a 26 *acres* plant to be Rs 2.3 billion (14.7 million USD).

3.8.2 Area Cost for Landfill Gas to Energy Technology

The formula used for calculation of area required for area of a landfill plant is given as follows:

$$Area = \frac{landfill\ capacity}{0.9} \times landfill\ height \tag{29}$$

Here, the height of landfill is taken as 20*m* and the formula for landfill capacity is given below:

$$Landfill\ capacity = V_w + V_c + V_d - V_s \tag{30}$$

Here, V_w is the total volume of waste over the lifetime of landfill (20 years), V_c is the total volume of cover system, V_d is the total volume of daily cover in 20 years and V_s is the free volume that will be available after 10 years due to settlement and biodegradation of the waste.

$$V_d = 0.1V_w \tag{31}$$

$$V_c = kV_w \tag{32}$$

$$V_s = mV_w \tag{33}$$

Here, the value of k is taken as 0.125 and m is degradation constant the value of which is 0.1 for biodegradable waste.

The total area for landfill is calculated to be 160 acres which makes the cost required for land area to be Rs 14 billion (89.7 million USD).

3.9 Economic Analysis of Biogas Recovery Technologies:

In order to find out the economic feasibility and sustainability of a project some economic parameters need to be measured. These parameters include Levelized Cost of Energy (LCOE), Total Life Cycle Cost (TLCC), Net Present Value (NPV), Payback Period (PBP) and Internal Rate of Return (IRR). The values of these parameters will determine the scope and future of the project and whether the project is worthy of a hefty investment or not.

3.9.1 Total Life Cycle Cost

Total Life Cycle Cost is a very important factor for determining the economic viability of an investment project. It is basically an aggregate of all the costs (both investment and Operation & Maintenance costs) over the lifetime of the project. TLCC is the sum of capital cost C_{inv}, Operation & Maintenance costs (C_{OM}) and the yearly cost of landfilling residual waste C_r. following equation is used for the calculation of TLCC of both Anaerobic Digestion and Landfill Gas to Energy technology.

$$TLCC_i = C_{inv(i)} + \sum_{n=1}^{N} \frac{C_{OM(i)} + C_r}{(1+d)^n} \tag{34}$$

Here, i is the type of energy recovery technology which could be Anaerobic Digestion or Landfill Gas to Energy technology.

d is the nominal discount rate and its value is taken as 6.25% (IMF 2017). The discount rate is a very important factor for calculating the economic parameters. The economic parameters such as TLCC, IRR, NPV and specially LCOE are affected by the variation in the discount rate. Generally, the value of discount rate for any type of investment varies between 3 to 10% (IRENA 2012). When the value of discount rate is less than 10% as in our case the biomass based energy sources become more profitable and attractive.

3.9.2 Levelized Cost of Energy

Levelized Cost of Energy is a very important parameter in economic analysis and it serves as the basis for measuring two technologies in order to determine which technology is more feasible. LCOE is a minimum cost of energy for which the capital cost of the project becomes equal to the Operation & Maintenance cost and it is measured in *USD / kWh*. The value of LCOE can be calculated for each technology by using the following equation:

$$LCOE_i = \left(\frac{TLCC_i}{\sum_{n=1}^{N} \frac{E_{p(i)}}{(1+d)^n}} \right) \tag{35}$$

If the value of LCOE for one technology is smaller than the other it means that this technology is more economically feasible as compared to the other one.

3.9.3 Net Present Value

The Net Present Value of a project is determined by finding the difference between the current value of the total costs that the system will incur over its lifetime and the present value of all the income that it earns over its lifetime. In simple words it is the difference between the cash inflows and cash outflows over the lifetime of the project. Cash inflows mainly includes the revenue and other benefits such as subsidies, incentives and tax remission. On the other hand, the cash outflows consist of investment cost, O&M cost, income tax etc. For a project to be economically feasible the value of NPV should be positive meaning that the cash inflows should be greater than the cash outflows. The formula used for the calculation of NPV is given below:

$$NPV_i = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} \tag{36}$$

$$F_n = Rev - C_{inv} - C_{OM} - C_{tax} \tag{37}$$

$$Rev = E_p \times F_d \tag{38}$$

$$C_{tax} = (Rev - C_{OM}) \times T_{rate} \tag{39}$$

$$d_r = \left(\frac{1+d_n}{1+e_{inf}}\right) - 1 \tag{40}$$

Here, C_{tax} is the taxable income which is the amount of tax paid on the profit that is gained from the project, Rev is the revenue made from the investment, F_d is the feed in tarrif value for the sale of electricity, T_{rate} is the marginal tax rate, d_r is the annual real discount rate and e_{inf} is the inflation rate. The value of F_d, T_{rate} and e_{inf} is taken as 10.31 *USD / kWh*, 29%, and 9.4% respectively.

3.9.4 Internal Rate of Return

Internal Rate of Return is that value of nominal discount rate which gives an NPV of zero when applied to the after-tax cash flow over the lifetime of project. For a project to be economically feasible the value of IRR should be greater than the target value and it should never be equal to zero. The value of IRR requires to be determined through an iterative process. We found it by using an IRR calculator available online (calculatorstuff.com).

3.9.5 Payback Period

Payback Period is defined as the time in years after which the investment cost breaks even which means that capital cost becomes equal to Operation & Maintenance cost. After the PBP a return on the investment starts. PBP is calculated by using the following equation:

$$PBP_i = \frac{TLCC_i\ (USD)}{C_{saved(i)}\ \left(\frac{USD}{year}\right)} \tag{41}$$

$$C_{saved(i)} = Rev_i - C_{OM(i)} \tag{42}$$

Here, C_{saved} is the amount of cost that is saved by generating revenue from the project. The smaller the value of PBB the more feasible the project is as it will start generating revenue in less time.

3.10 Sensitivity Analysis

The parameters for economic analysis of a project vary on the basis of different factors such as capacity factor, waste collection rate and per capita waste generation rate, thus affecting the economic viability of the concerned project. Sensitivity analysis is conducted in order to determine the impact of these factors on the economic viability of both waste to energy projects.

3.10.1 Capacity Factor

Capacity factor of plant is defined as the ratio of the actual amount of waste (*tons*) that is being treated to the amount of waste (*tons*) that could be treated if the plant were operating at its maximum capacity, which means that it was operated throughout the year (8760 *hours*) without any breaks. It is possible only under ideal scenario as the plant operation in real life is often limited by the availability of feedstock and other Operation and Management issues. The capacity factor of the plant might also vary with seasons as it effects the availability of feedstock. The capacity factor for both technologies is varied between 60 to 90% and its effect on the economic parameters, TLCC, LCOE, NPV and PBP, are determined using the equations 34, 35, 36 and 41.

3.10.2 Waste collection rate

The waste collection rate is the rate at which solid waste is collected from the collection sites and then transferred to the treatment site. It is a very important factor that effects the economic parameters and it depends on the development and economy of the area, the current waste collection rate for Islamabad is very high but it may vary with time. In order to determine the influence of changing waste collection rate on the economic parameters it is varied between 65 to 95% and the results are calculated using the equations 34, 35, 36 and 41.

3.10.3 Per Capita Waste Generation Rate

The per capita waste generation is a factor that is bound to change over the lifetime of the project as it is highly influenced by the population and economy of the area, and there is no doubt that the population of the city will increase with time resulting in economic growth thus, leading to more waste generation. The value for waste generation per capita is varied between 0.4 and 0.8 (*kg/capita/day*) and its effect on the economic parameters is determined using the equations 34, 35, 36 and 41.

3.11 Environmental Evaluation

The purpose of conducting environmental assessment of a project is to determine its positive as well as negative impacts on the environment throughout its lifetime. In case of Anaerobic Digestion and Landfill Gas to Energy technology we consider the impacts resulting from the generation of biogas from both processes and then the burning of biogas as an alternative to fossil fuels for electricity generation.

3.11.1 Greenhouse Gas emissions

In case of both the technologies methane gas is the only GHG that is considered to determine the global warming potential of the technologies. The CO_2 which is removed after cleaning of biogas and is also released from the combustion of biogas is not considered a greenhouse gas but carbon neutral keeping in mind its biogenic origin. Other GHG components that are released in minor quantities are also ignored while determining the global warming potential. The global warming potential of the methane gas is measured relative to the CO_2. The formulas used for the calculation of global warming potential for both AD and LFG technology are given below:

$$AD_{GWP}\ (kgCO_2) = CH_4 \times 5\% \times GWP(CH_4) \times \rho_{CH_4} \tag{43}$$

$$LFG_{GWP}\ (kgCO_2) = LF_{CH_4} \times 25\% \times 6.67 \times 10^{-4} \times GWP(CH_4) \times 1000 \tag{44}$$

The leakage factor for Anaerobic Digestion and LFG technology is taken as 5% and 25% respectively. The GWP of methane is taken as 25 *kg* CO_2 */ kg* CH_4 and the density of methane ρ_{CH_4} at STP is 0.717 kg / m^3.

3.11.2 Diesel Displacement with Equivalent of Biogas

Diesel is being replaced by biogas in internal combustion engines resulting in the decrease of GHG emissions. The amount of diesel fuel that is being displaced by the biogas is calculated by using the following formula:

$$F_{d(i)} = 0.246 \times P_i + 0.08415 \times P_G \tag{45}$$

Here, F_d is the amount of diesel being replaced by biogas (*liters*), i is the type of technology, P_G is the internal combustion engine's power rating (*kW*) and P_i is the power rating (*kW*)of technologies.

Chapter 4

4 Results and Discussion

4.1 Waste Generation Potential from Islamabad

Figure 4.1 provides data for projection of municipal solid waste generation in Islamabad over a period of 21 years, i.e. assuming in 1 year is the design and construction will be completed and project will have 20 years of operation which is the project lifetime.

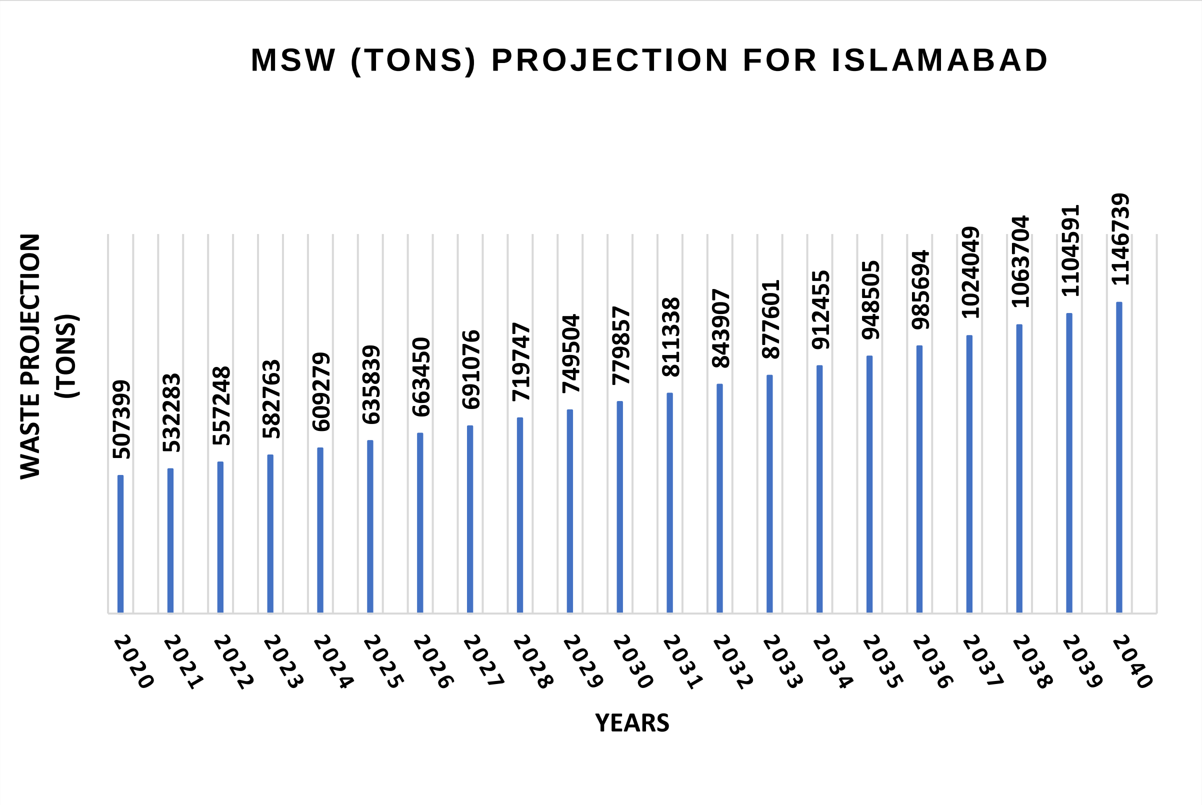


Figure 4.1: MSW projection for Islamabad from 2020-2040

The results are found using the population data provided by Pakistan Bureau of Statistics (PBS, 2017) along with per capita waste generation rate which is found from an original publication (Zia et al., 2017). The findings of the figure are that in 2020, about 507,399 tons, is generated and it is expected to rise to about 1,146,739 tons in 2040. The difference being of 639, 340 tons giving an increment of 126.0% in waste generation in Islamabad over 21 years period. Economic growth and increasing population contribute to this high quantity of waste generation.

4.2 Methane yield and electricity generation potential from AD and LFG technologies

The methane yield for each of the two technologies is found over the period of 21 years and the results are presented in Table 4.1 and Figure 4.2. During 21 years period, AD technology methane recovery potential ranges between 126.6–286.1 m^3/y while LFG technology can generate 1.6–39.7 m^3/y. On the whole, an increase in yield is observed throughout the year for both the technologies as the quantity of waste increased. It can also be deduced from the results that significantly higher methane yield is observed for the digester based plant in comparison to the other technology.

Depending on the results of biogas recovery, electricity generation potential results are obtained for each technology (Table 4.2 and Figure 4.3). The range of electricity generation for AD technology is found to be 400.3–904.8 GWh/y while for LFG technology it is 3.5–84.8 GWh/y. The similar trend is seen in the results as in methane yield such that the electricity generation increased over the years for both technologies. The electricity generation potential is also found to be much higher for AD technology as on average, about 629.2 GWh/y of electricity is generated is observed for AD technology as compared to average value of 42.1 GWh/y for LFG technology.

Given the average electrical energy potential of the two plants, average plant sizes were computed for of digester plant and landfill gas plant as 71.8 MW and 4.8 MW.

Table 4.1: Methane yield for Islamabad from 2020 to 2040

Years		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Vol of Methane × 10^6 (m^3/y)	**AD**	126.6	132.8	139.0	145.4	152.0	158.6	165.5	172.4	179.6	187.0	194.6
	LFG	1.6	3.3	4.9	6.6	8.4	10.1	11.9	13.6	15.4	17.3	19.1
Years		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	
Vol of Methane × 10^6 (m^3/y)	**AD**	202.4	210.5	219.0	227.6	236.6	245.9	255.5	265.4	275.6	286.1	
	LFG	21.0	22.9	24.9	26.9	28.9	31.0	33.1	35.2	37.4	39.7	

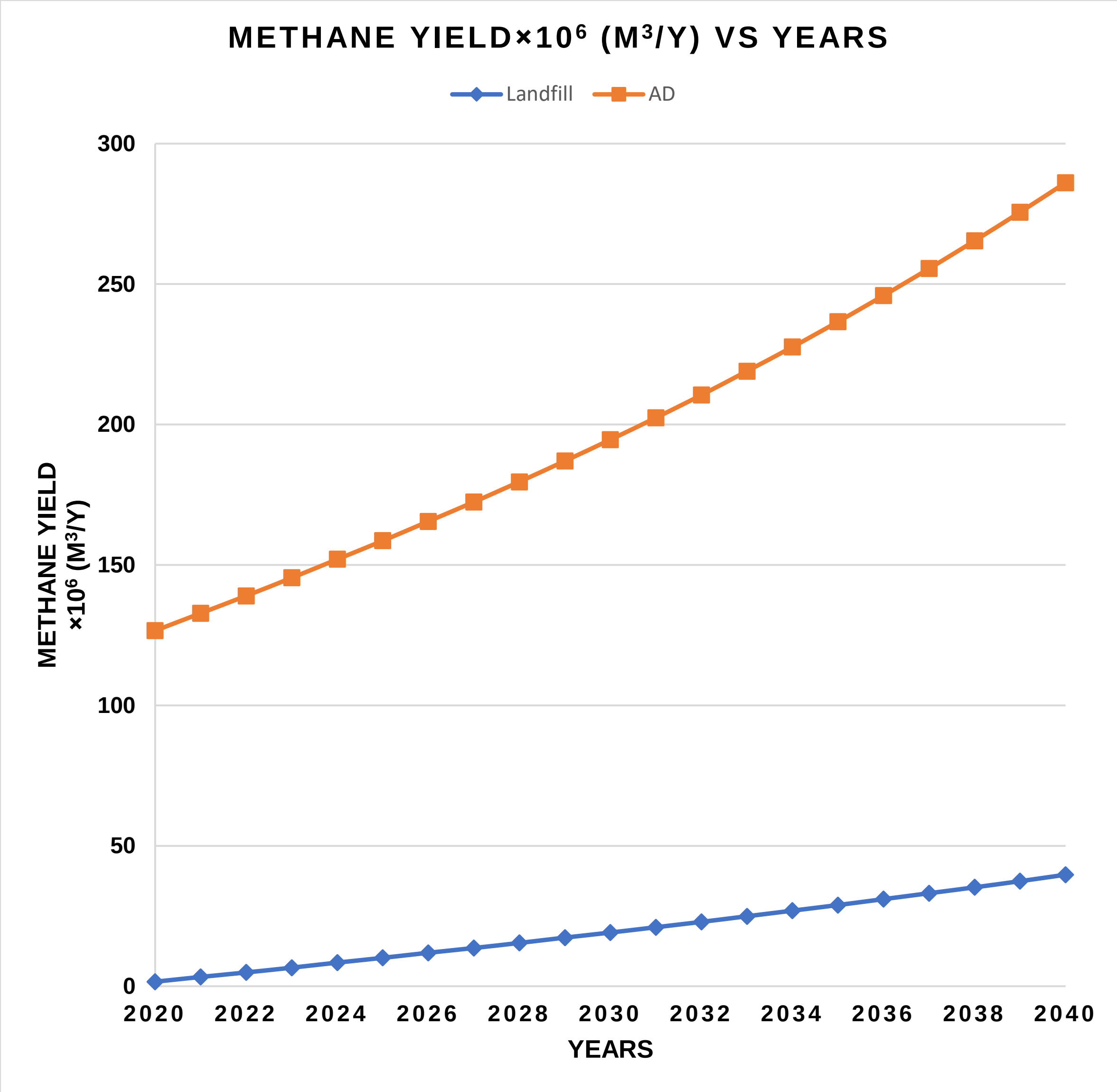


Figure 4.2: Methane Yield for Islamabad from 2020 to 2040

Table 4.2: Electricity Generation for Islamabad from 2020 to 2040

Years		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Electricity Generation (GWh/y)	**AD**	400.3	420.0	439.7	459.8	480.7	501.7	523.5	545.3	567.9	591.4	615.3
	LFG	3.5	7.0	10.6	14.2	17.9	21.6	25.4	29.2	33.0	36.9	40.9
Years		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	
Electricity Generation (GWh/y)	**AD**	640.1	665.8	692.4	719.9	748.4	777.7	808.0	839.3	871.5	904.8	
	LFG	44.9	49.0	53.2	57.4	61.7	66.1	70.6	75.2	80.0	84.8	

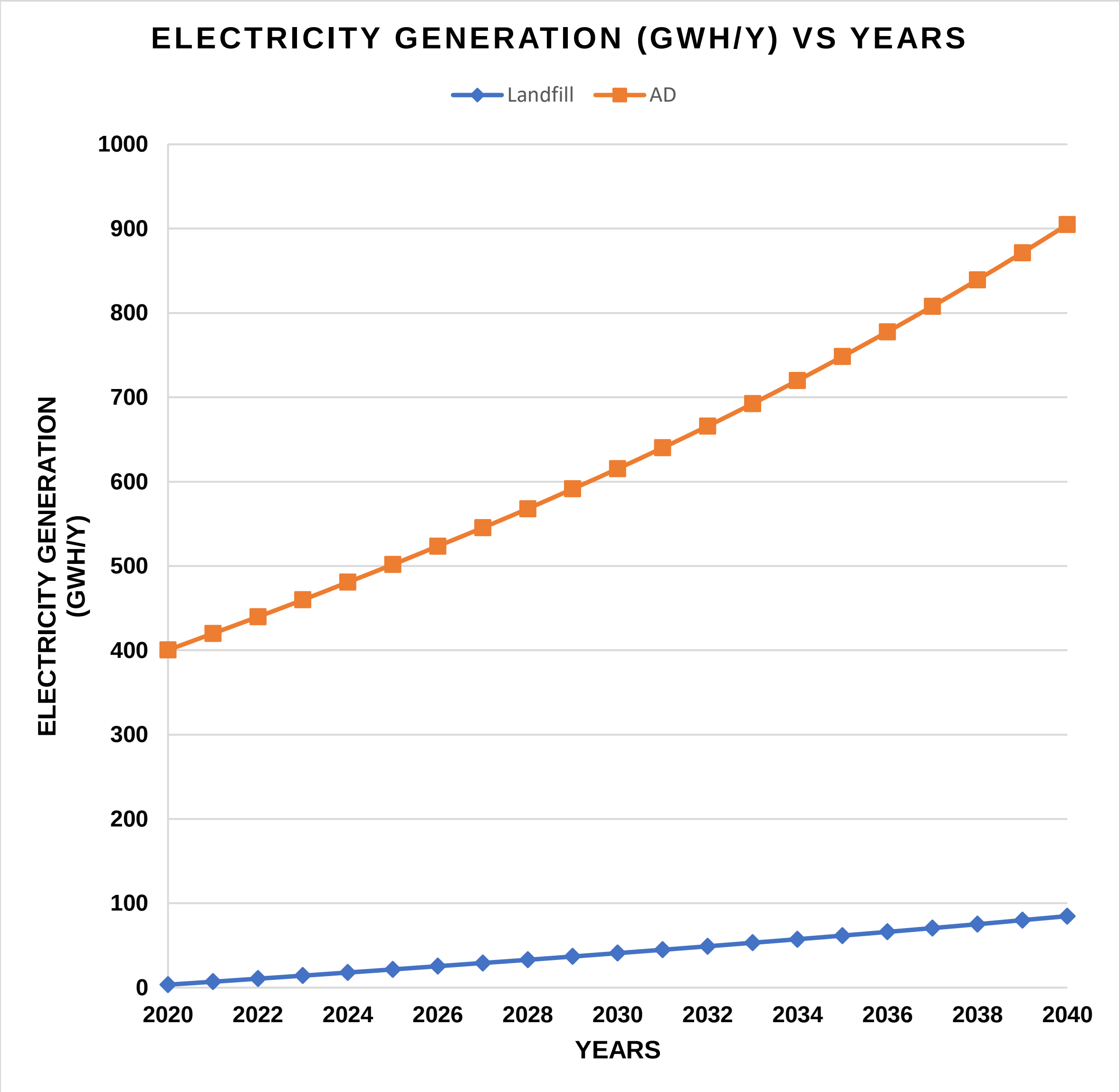


Figure 4.3: Electricity Generation for Islamabad from 2020 to 2040

4.3 Economic Assessment of the technologies

The economic parameters used for the feasibility assessment are Total Life Cycle Cost (TLCC), Levelized Cost of Energy (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). LCOE was evaluated yearly while the remaining parameters are determined over the whole 21 years period.

LCOEs are found for both technologies (Table 4.3) and results depict that the values decrease over the project period. This is computed based on the fact that electricity generation potential depends on methane yield which further depends on the feedstock availability. Therefore, as the feedstock is bound to increase every year so more waste to energy conversion is possible with the passage of time. The average LCOE for the digester and landfill gas plants are 0.0170 USD/kWh and 0.0384 USD/kWh.

Both technological implantations are viable (Table 4.4), according to all given parameters with exception to IRR. The IRR for AD technology is found to be positive and higher than nominal discount rate. On the other hand, IRR obtained for LFG technology is negative and, hence, less than nominal discount rate which indicates that this technology is financially unfeasible. The NPV value is positive in case of both technologies but is more positive for AD technology with a lower return period of around 6 years. Therefore, the anaerobic digester technology should be opted between the two technologies due to its more promising outcomes. Despite of such encouraging indications for AD technology in Islamabad, it has been given very little attention which may be due to high capital cost required, dearth of technical skills and experience to operate AD plants using Organic fraction of Municipal Solid Waste in Islamabad.

Table 4.3: Levelized Cost of Energy for Islamabad from 2020 to 2040

Years		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
LCOE (USD/ kWh)	**AD**	0.0312	0.0204	0.0198	0.0192	0.0187	0.0182	0.0177	0.0173	0.0169	0.0164	0.0161
	LFG	0.0886	0.0676	0.0532	0.0461	0.0417	0.0389	0.0368	0.0353	0.0341	0.0331	0.0323
Years		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	
LCOE (USD/ kWh)	**AD**	0.0157	0.0154	0.0150	0.0147	0.0144	0.0141	0.0138	0.0136	0.0133	0.0131	
	LFG	0.0317	0.0311	0.0306	0.0302	0.0298	0.0295	0.0292	0.0290	0.0288	0.0285	

Table 4.4: Economic Potential for Islamabad from 2020 to 2040

Economic parameters	**AD Technology**	**LFG Technology**
Total Life Cycle Cost (million USD)	208.7	38.0
Net Present Value (million USD)	691.0	43.0
Internal Rate of Return (%)	9.3	–4.3%
Payback Period (years)	6	20

4.4 Environmental Evaluation

Captive power plants are often used in Pakistan due to inadequate supply of energy. Thereby, several industrial consumers have to generate their independent power and often use diesel generators. If this diesel is displaced by methane obtained from either AD or LFG technology, total savings in CO_2 eq GHG emission of 8777.08 ktons and 334.77 ktons can be obtained (Table 4.5 and Figure 4.4) which are crucial given that the world has the challenge to combat climate change.

The LCA method used for determining global warming potential (GWP) based on the CO_2 equivalent GHG emissions of methane production from each of the two technologies is evaluated (Table 4.6). It is found that the contribution of AD towards GHG emissions is 3745.57 ktons of CO_2 eq while for LFG it was 1727.01 ktons for the entire period of 21 years. This reveals that LFG technology would be preferred if solely environment is concerned.

Table 4.5: GHG Savings if methane displaces diesel for Islamabad from 2020 to 2040

Years		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
M_d (ktons)	**AD**	265.93	278.97	292.05	305.43	319.32	333.24	347.71	362.19	377.22	392.81	408.72
	LFG	1.33	2.68	4.04	5.41	6.80	8.20	9.62	11.06	12.52	13.99	15.49
Years		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	
M_d (ktons)	**AD**	425.22	442.29	459.95	478.22	497.11	516.60	536.70	557.49	578.91	601.00	
	LFG	17.01	18.57	20.14	21.75	23.39	25.06	26.77	28.51	30.30	32.12	

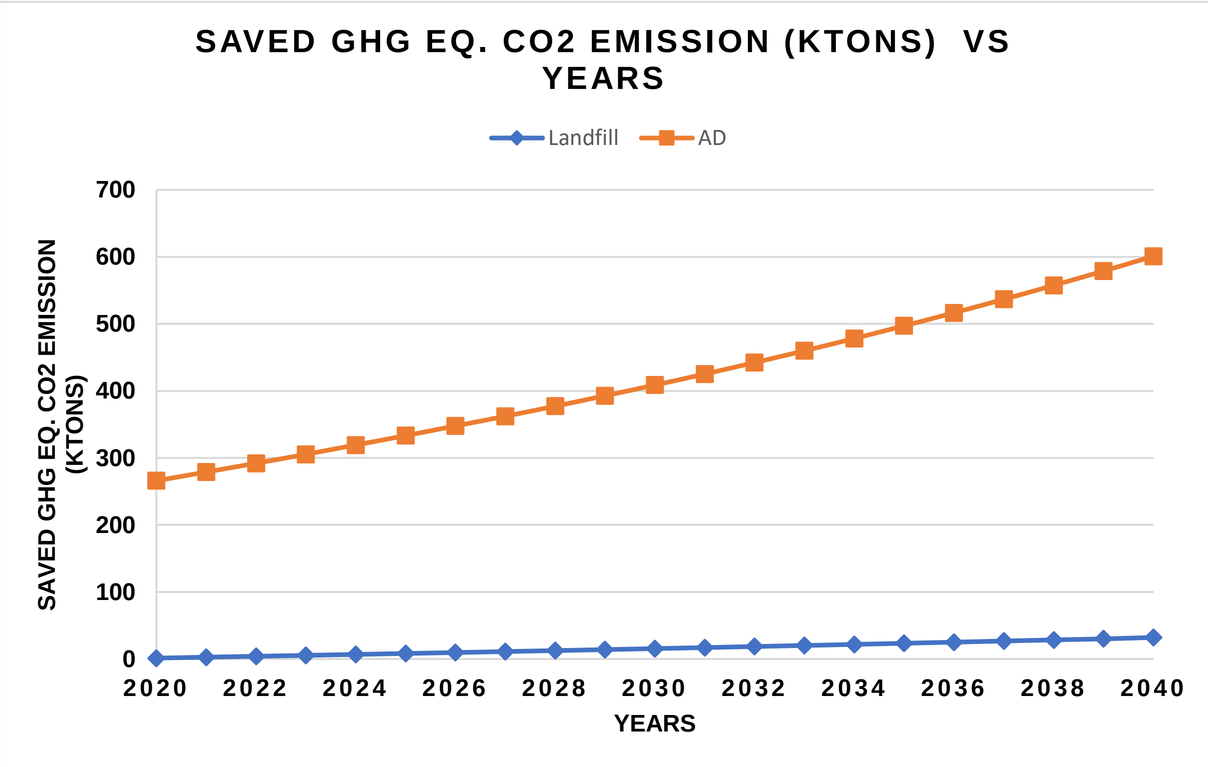


Figure 4.4: GHG Eq. CO_2 emission Savings if methane displaces diesel for Islamabad from 2020 to 2040

Table 4.6: Global Warming Potential for Islamabad from 2020 to 2040

Years		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
GWP (ktons)	**AD**	113.48	119.04	124.63	130.33	136.26	142.20	148.38	154.56	160.97	167.63	174.41
	LFG	6.87	13.81	20.82	27.90	35.06	42.31	49.64	57.07	64.57	72.20	79.91
Years		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	
GWP (ktons)	**AD**	181.46	188.74	196.28	204.07	212.13	220.45	229.03	237.90	247.04	256.47	
	LFG	87.79	95.79	103.92	112.22	120.64	129.27	138.06	147.07	156.28	165.70	

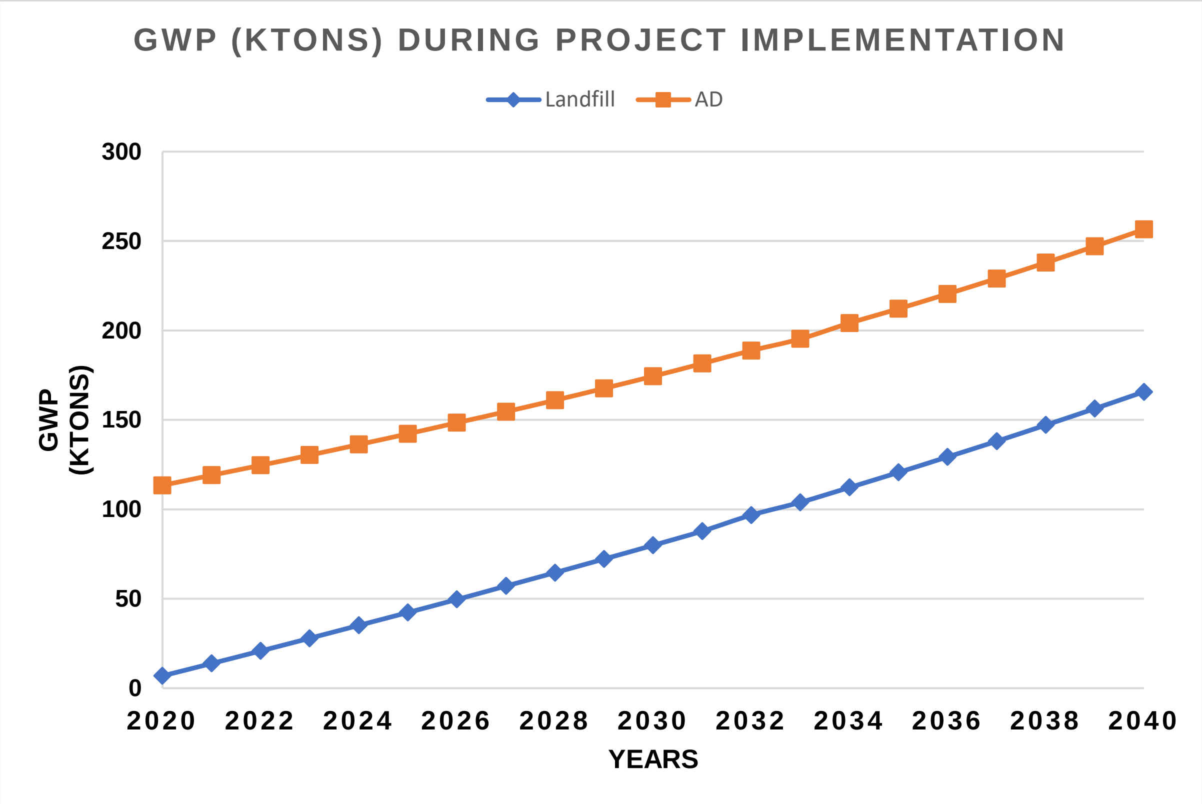
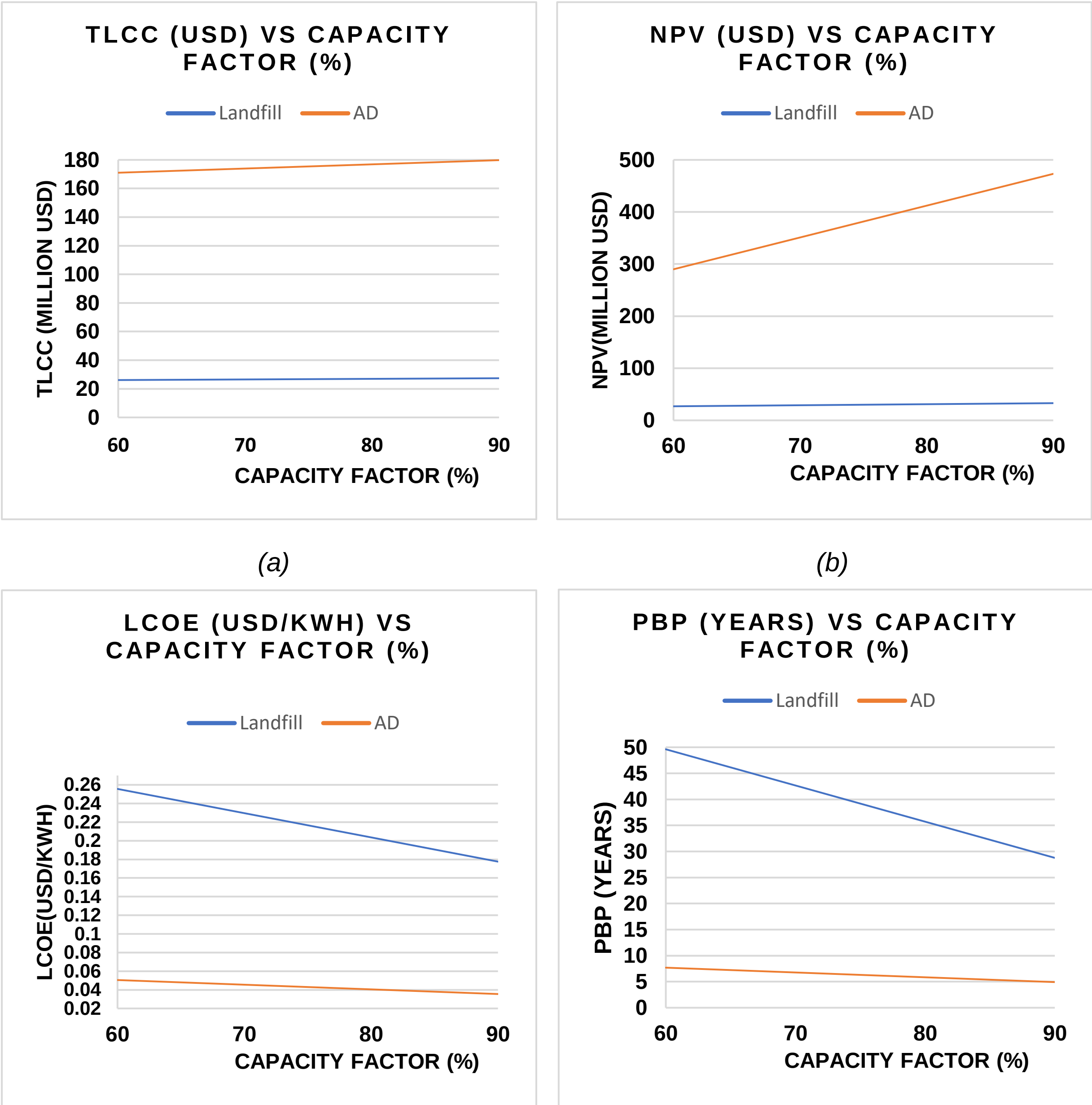


Figure 4.5: Project Global warming potential for Islamabad from 2020 to 2040

4.5 Sensitivity Analysis to determine changes in economic viability based on changes in input variables

Sensitivity analysis depicts variation in the target variable (i.e. economic parameters in this case) based on the input variables. This chapter aims to provide the information on the influence of capacity factor, waste collection rate and waste generation rate over the economic feasibility of the two plants. Thus, the relationship between financial parameters and sensitivity variables is investigated for both waste-to-energy plants.

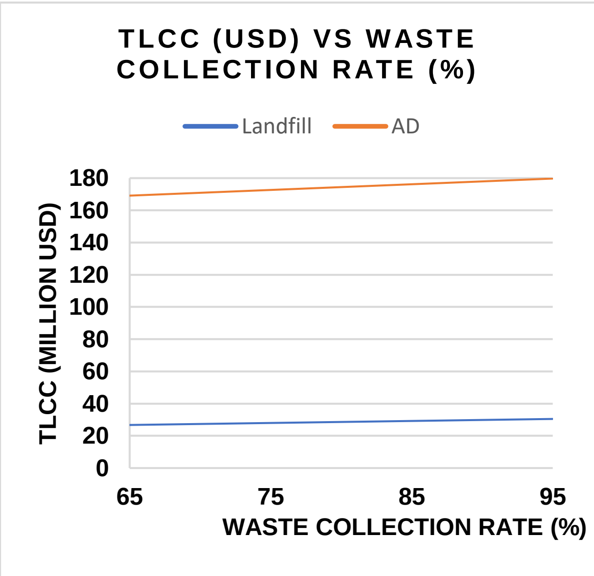
Figure 4.6 provides summary of results of economic parameters when capacity factor is varied between 60–90%. For TLCC and NPV, there is a minimal increase for LFG technology while marginal increase is observed in TLCC along with a sharp increase in NPV for AD technology. Overall, a better increasing trend is observed for the latter technology in the case of these two parameters. For other two parameters, LCOE and PBP, significant decrease is observed for LFG technology while marginal decrease is observed for the other technology.



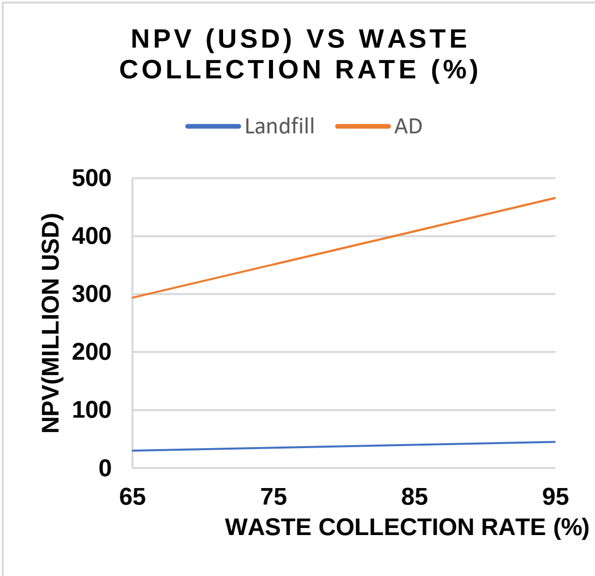
(c) (d)

Figure 4.6: Influence of capacity factor on (a) TLCC (b) NPV (c) LCOE (d) PBP

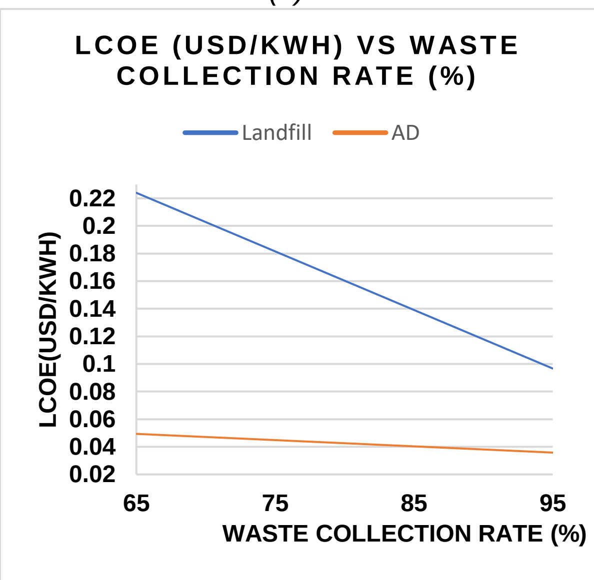
Figure 4.7 provides summary of results for the influence of waste collection rate on economic parameters when it is varied from 65 to 95%. For TLCC and NPV, there is a very slight increase for LFG technology was observed while marginal increase is observed for AD technology in its TLCC along with a sharp escalation in NPV. Overall, a better increasing trend is observed in the case of AD technology. For other two variables, LCOE and PBP, a significant decline is observed for LFG technology while a slight decrease is observed for the other technology.



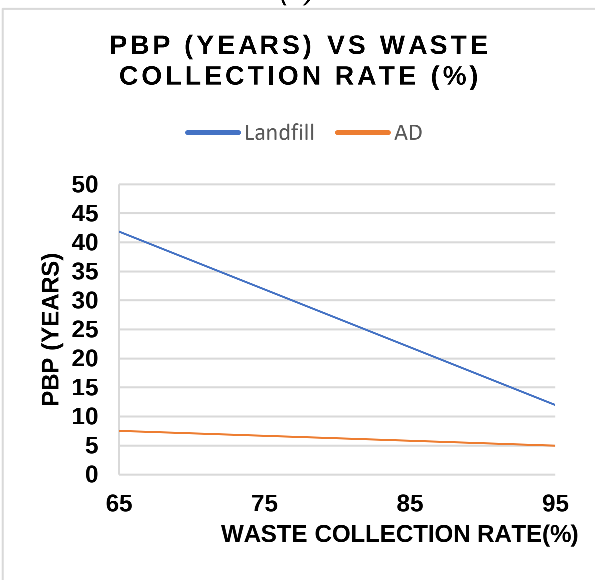
(a)



(b)



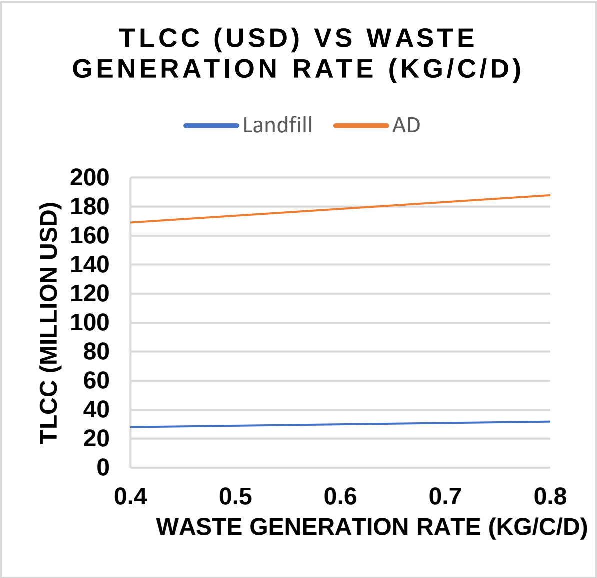
(c)

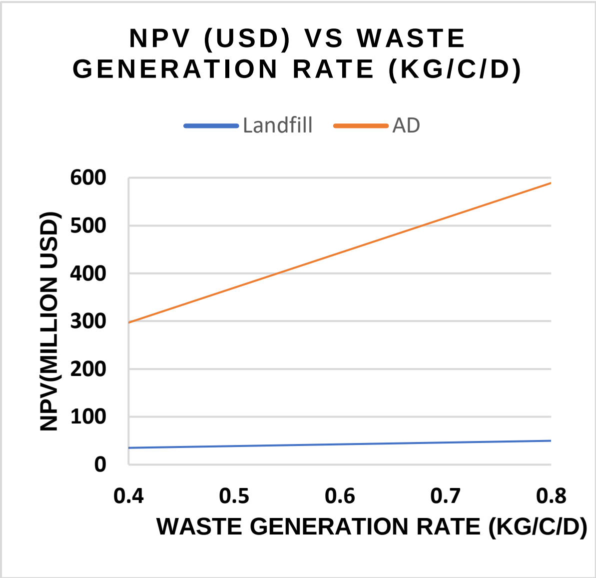


(d)

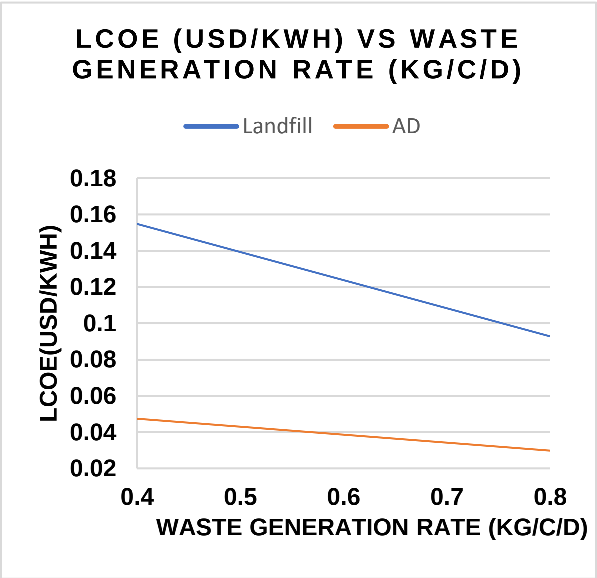
Figure 4.7: Influence of waste collection rate on (a) TLCC (b) NPV (c) LCOE (d) PBP

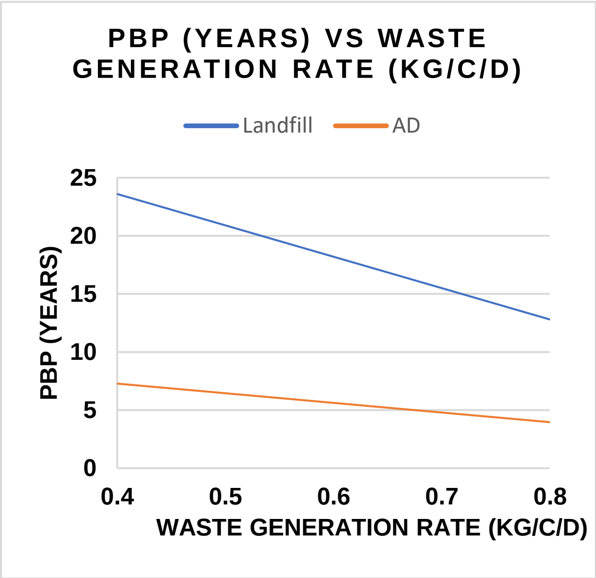
The influence of waste generation rate in the range of 0.400 to 0.800 kg/c/d on financial parameters is determined (Figure 4.8). For TLCC and NPV, there is a minimal increase for LFG technology while the TLCC for AD technology increased slightly and its NPV observed a sharp increase. These results reveal that a better increasing trend is observed for the latter technology in the case of these two variables. For both technologies, the other two parameters, LCOE and PBP, are observed to decline although sharper decrease was observed for LFG technology.





(a) *(b)*





(c) *(d)*

Figure 4.8: Influence of waste generation rate on (a) TLCC (b) NPV (c) LCOE (d) PBP

Sensitivity analysis results obtained by variation of all three variables, namely, capacity factor, waste collection rate and waste generation rate reveal that economic viability of AD technology is more promising as higher positivity for NPV and lower LCOE and PBP were obtained as compared to LFG technology.

Chapter 5

5 Conclusion

A comprehensive study has been conducted to assess the bioenergy potential, economic sustainability and ecological benefits offered by anaerobic digestion and landfill gas energy implantations through conversion of organic composition of municipal solid waste to electrical energy (i.e. waste to energy) has been conducted. Diesel displacement by methane produced from either of the two technologies and lifecycle assessment tool are used to carry out environmental evaluations. Sensitivity analysis enabled to examine the influence of particular variables on the overall economy of the project. It is established from the results that both the technologies can significantly contribute to the energy mix of Islamabad. The average electricity generation for AD technology is found to be 629.2 GWh, whereas, 42.1 GWh is found to be the average electricity generation from LFG technology if operated at 36% electricity conversion efficiency. The AD technology is proved to be economically viable as with positive net present value, low return period of 6 years and higher internal rate of return than the discount rate of 6.25%. On the other hand, LFG implantation is not economically feasible as, even though it has positive net present value, but the high payback period of 20 years and negative internal rate of return presents it to be not feasible. Levelized cost of energy for both technologies are low and are in close relation to (IRENA, 2019) which is again a positive result. Environmental benefits offered by saving CO_2 equivalent greenhouse gas by displacing diesel by methane produced from each of the two technologies where AD technology has more potential of savings than LFG technology. It is also to be noted that the former produces higher CO_2 eq. greenhouse gas emission throughout its operation which may be due to very high methane yield production as compared to landfill gas. The methane yield from LFG technology in Islamabad are lower as compared to other studies, for instance, (Ayodele, 2018) which may be due to seasonal variation and different soil characteristics. In conclusion, energetic and economic perspectives prove digester plant as the better option in comparison with the other technology. Additionally, with growing innovation in technologies the methane leakage factor of 5% may be controlled to achieve lesser AD plant emissions than LFG plant in future. This study will encourage the investors in making better decisions while opting for any one of these technologies.

Chapter 6

6 Recommendations

The project study is conducted to investigate the potential of two waste-to-energy (WtE) technologies: anaerobic digestion (AD) and landfill gas technology for Islamabad. However, there are some limitations which need to be taken account in future. Thus, few recommendations are as under,

- Future studies need to consider the variations in composition of waste, moisture content, efficiency of gas collected in landfill and conversion technologies which were assumed to be constant during the study period.
- Other Environmental factors like acidification potential, dioxin/furan emission and land use to be considered in future.
- Use more sensitivity analysis variables to further study the economic viability which may include discount rate, electricity generation efficiency, capital cost and so on.

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