Economic and Environmental Feasibility for Electricity Generation using Biogas from Organic Fraction of Municipal Solid Waste for Lahore

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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Environmental Science

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Dedication

This research is dedicated to my loving, caring, and industrious parents, whose efforts and sacrifice have made my dream of having this degree a reality. Words cannot adequately express my deep gratitude to them.

"O My Sustainer, Bestow on my parents your mercy even as they cherished me in my childhood".

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TABLE OF CONTENTS

List of Abbreviation or Keywords

AD	Anaerobic Digestion
DOC	Degradable organic carbon
GWh	Giga watt hour
GWP	Global warming potential
ICE	Internal combustion engine
IRR	Internal rate of return
LCOE	Levelized cost of energy
LFGR	Landfill gas recovery technology
MCF	Methane correction factor
MSW	Municipal solid waste
NPV	Net present value
PBP	Payback period
S_C	Social cost
TLCC	Total life cycle cost
USD	United states dollar

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ABSTRACT

In this study, the electricity generation potential of methane gas recovered from anaerobic digestion (AD) and landfill gas (LFG) technology, treating municipal solid waste (MSW) of Lahore is analyzed. The same data was used for economic and environmental assessment of both technologies, in Lahore, Pakistan. For economic assessment of both technologies, the important financial indicators such as, total lifecycle cost (TLCC), levelised cost of energy (LCOE), net present value (NPV), internal rate of return (IRR) and payback period (PBP) were used. The above economic parameters are also calculated with addition of avoidable cost of negative environmental externalities (i.e., social cost of CH4 release from landfill sites if the energy recovery system is not installed). Sensitivity analysis for AD technology is also conducted by varying the currency (USD vs PKR) exchange rate, feed on tariff and marginal tax rate, to determine their impacts on economic viability of technology. The environmental assessment is also carried out by estimating the GWP of both technologies under three different scenarios for 20 year projects life. Results of the study show that from 2021 to 2040, the total MSW generation potential of Lahore city is 14450 ktons. The electricity generation potential of AD and LFG technologies are 132477 and 4056 GWh respectively. Economic indicators shows that AD technology is economically viable, while LFG technology is not viable for the area under study in given conditions (inputs). But, with the addition of monetarized cost of externalities, both AD and LFG technology are economically viable. The AD technology gives positive NPV and IRR which are 616.6 million USD and 1.86% respectively, while the NPV and IRR calculated for LFG technology is negative which are -650 million USD and -8.8% respectively. The average LCOE for AD and LFG technology over the life span of projects are 0.0409 and 0.1376 USD/kWh, respectively. The PBP for AD technology is 17.8 years while the LFG technology couldn't recover its initial expenses in given time span. The profitability of both technologies enhances with the addition of externalities cost. The NPV of AD and LFG technologies with the addition of externalities are 3139 and 366 million USD, respectively, while the IRR increases to 6% and 4.4% for AD and LFG technology, respectively. Environmental assessment shows the GWP of LFG technology is higher than that of AD technology, which is 1808 and 292 tons CO_2-eq, respectively, for the generation of one GWh electricity.

CHAPTER 1

1. INTRODUCTION

The concept of sustainable development has become prominent in recent years, among the global community (Maria et al., 2020). Different factors like urbanization, increasing population and rapid economic growth have increased the consumption of natural resources, which adversely affect the environment. These issues contribute to the generation of huge quantity of municipal solid waste (MSW) that is going into the environment (Singh et al., 2017). Global waste generation per day is 2.1 billion tons (Naveed et al., 2022). World-widely, the improper disposal of MSW caused many socio-economic and environmental problems. So, this is an emerging challenge for world in recent decades to sustain the standard life pattern.

All the man made and natural processes in the world need energy and its flow from one form into another that's why the energy has an important role in economic development and wellbeing of mankind. Globally, about 80% of energy is derived from hydrocarbons in the form of coal, oil, and gas (muller-furstenberger and wager, 2018). With the passage of time, fossil fuel reserves of the world are depleting, and energy demand is increasing due to rapid population growth and enhancement in the lifestyle of masses. Therefore, to meet this increasing demand, other renewable energy resources are needed by the world (Ball et al., 2017).

Municipal solid waste (MSW) consists of refused waste that generates from markets, households, yards or gardens, parks, street sweepings etc. The main source of municipal solid waste generation are residential and commercial complexes (Amoo et al., 2013). The broader classification of typical MSW is organic and inorganic compounds. The organic waste in MSW consists of biodegradable and non-biodegradable materials. The rate of MSW generation is highly depends upon the population, per capita waste generation rate, industrialization, income of pupil, socio-economic status of masses and types of commercial activities that are common in the area (Kuang and Lin. 2021).

Mismanagement of MSW is a huge issue facing by the world in present time. Moreover, the urban environment is deteriorating due to mismanagement of this huge quantity if MSW generates in urban centers of the world. So, to overcome this issue, the MSW has to be managed and should be used in energy recover technologies to generate energy (Olaleye and Richard, 2013). Furthermore, the over exploitation of fossil fuel reserves to generate electricity has caused many environmental calamities like global warming and climatic changes. This all is due to excessive emissions of greenhouse gases (GHGs) from fossil fuels, used as energy sources for many decades. Currently, the GHG emissions are considered as most threatening issues for environment and mankind (Ayodele et al., 2017). Due to significant environmental threats and rapid depletion in fossil fuel reserves, the global attentions are shifted towards the renewable energy resources and efficient technologies for the purpose of electricity generation and transportation. Recently, in past decades the concept of energy recovery from MSW is gaining more attraction because it is sustainable energy source while the energy recovery from fossil fuels is not sustainable and GHGs emissions from it had already caused many environmental problems (Teodor et al., 2012).

Like many countries, Pakistan is also facing the problem of excessive MSW generation annually in its urban centers. About 71000 tons of MSW generates per day in Pakistan (Khatri et al., 2021). This MSW has about 56.2% of organic fraction, which can be used in anaerobic technologies to generate energy from this MSW (Azam et al., 2020).

Currently many municipal solid waste management techniques are devised globally for proper management of MSW. Among them, some common methods are Solid waste open burning, Anaerobic digestion of MSW, engineered landfill gas recovery technology, Sea dumping process, solid wastes sanitary landfills, Incineration of MSW, Composting process, Disposal by Ploughing into the fields, Disposal by hog feeding, and Salvaging procedure (Muhammad et al., 2021).

Anaerobic digestion (AD) and landfill gas recovery (LFG) technology has been identified as energy recovery technologies to generate energy from MSW. These technologies can help in energy generation as well as in municipal solid waste management in environmental-friendly and economically viable manners, to reduce gap between sustainable development and energy supply (Rajaeifara et al., 2017).

Many developing nations are showing interest in these technologies to generate energy from MSW and investigating waste-to-energy (wte) technologies to adopt them (Makarichi et al., 2019), while some European Union (EU) states have been successful in recovering energy from MSW by anaerobic digestion technologies. But so far, these technologies are in their initial stages and having lots of constraints of huge investment caused and technical demands required for these waste-to-energy technologies (Amsterdam et al., 2017). Additionally, the data regarding characteristics of generated MSW in urban centers is missing in most of the developing countries. This data is needed to analyze the feasibility of waste-to-energy technologies. Therefore, unavailability of this data in most developing countries also causes hindrance in adoption of these technologies (Masood et al., 2014).

Anaerobic digestion is a process in which the complex molecule of organic matter breaks down into simpler molecules by microorganisms, in the absence of oxygen. During this process methane generates that can be used in the generation of energy. The prominent stages in anaerobic digestion process are hydrolysis, acidogenesis, acetogenesis and methanogenesis. In each step diverse group of microorganisms (bacteria) interacts to carry out anaerobic digestion process. The gases, other than methane which are present in biogas are removed, so that, only methane can be used as an energy source to generate electricity (Cudjoe et al 2020).

Many countries like Sweden, Canada, France, Germany have developed such technologies that can be used for biogas recovery from the biodegradable part of municipal solid waste (Davis 2014). Among these technologies: anaerobic bio-digester, bioreactor landfill and dry-tomb landfill are prominent technologies for the generation biogas through anaerobically digestion process. The common aspect of these technologies is the biological decomposition of organic matter in absence of oxygen. In an aerobic degradation process many substrates can be used such as municipal solid waste, animal waste, wastewater, sludge from industries, agricultural waste, and residues for the generation of biogas (Aguilar-Virgen et al., 2014).

Anaerobic digester is an airtight biologically engineered structure, like the well-controlled enclosure or container, where biodegradable organic materials are placed. Anaerobic digester can be constructed using different materials such as steel, plastic, concrete, and wax (Ogunjuyigbe et al., 2017).

Among different types of reactors, the single stage batch reactor is easier to handle and economically viable, in which all the organic waste is loaded at once and all aforementioned stages takes place sequentially. The sludge is removed after the completion of process in the given retention period with maximum biogas generation (Meegoda et al., 2018).

Many options regarding selection of bio-digester all present there, but the choice of digester type is broadly depending upon number of factors which are moisture content, substrate feeding rate, the solid content in the feedstock, temperature, and economic constraints. The summary of these essential factors while selecting an aerobic digester are shown in Table 2.1.

In landfill gas (LFG) recovery technology the biodegradable landfill material is degraded in anaerobic conditions, under the influence of microorganisms. As a result of these an anaerobic microbial degradation, landfill gas generates, which consists of methane, carbon dioxide and other trace gases. Furthermore, a smaller portion of LFG (<0.5%), also contains non-methane organic compounds (Huang and Fooladi, 2021).

The fate of biogas generation from LFG technology changes overtime, in a typical engineered landfill. In first stage, the solid waste is placed in landfill without the biogas collection system, so mostly biogas emits into atmosphere except the amount of biogas which is oxidized in the soil cover. When the biogas collection systems are installed, a large portion of generated biogas is collected through a network of wells and connecting pipes, under negative pressure. However, the biogas collection efficiency ranges from sixty to ninety percent and even a sophisticated biogas collection system cannot collect all the biogas that produced in landfill under anaerobic microbial degradation of solid waste (Ruoso et al., 2022). As, the biogas had higher concentration of methane. So, its emission in atmosphere is serious threat to environment (Lizik et al., 2013).

There are many factors that influence the collection efficiency of landfill gas such as: designed and operation of LFG recovery system, composition of waste, thickness, soil texture and climate of the area. The fraction of biogas that is not collectable through biogas collection system can infiltrate into covering soil, which can be undergoes biological oxidation or release into atmosphere through preferential pathways such as, through the leakages in the landfill cap, pipe system, or through leachate collection system (Amini et al., 2013).

Biogas is the main product of anaerobic digestion and LFG recovery system. It consists of many gases but the prominent are methane (CH_4) and carbon dioxide (CO_2) which ranges from 55-75% and 25-45% by volume respectively. These both are most important greenhouse gases, and they have a huge contribution in global warming. Beside these, many other non-methane organic compounds such as hydrogen sulphide (H_2S), mercaptans, and other organic compounds.

In case of anaerobic digester, the reported methane concentration by volume is 55-70% and for landfill technology its concentration ranges 50-55% by volume. Furthermore, the energy content of methane is about 37.2 MJ/m^3 which make it an important component of biogas and it have a higher potential in generating electricity (Ayodele et al., 2017).

Biodegradable organic biomass is the input of both AD (bio digester) and LFG recycling technologies, both technologies follow different method to produce similar outputs (biogas or landfill gas). These two are different technologies, hence the cost of project implementation, the environmental benefits/burdens and the amount of biogas produced from two technologies would be different. The two technologies need to be compared and evaluated to be able to make a decision for choosing appropriate technology for a given location. Differences between the AD and LFG technologies are given in Table 2 (Ouda et al., 2016).

When a person's utility depends on both the activities under their controls and the activities of others, it is said that there is an externality. Externalities is said to be both positive and negative. Both production and consumption may have externalities; however, this study will focus on the positive externalities, where the utility of one producer of goods or services depends on the actions of the other producer (Zerrahn, 2017).

The social cost of carbon dioxide ($SCCO_2$) has become a common indicator for estimating the benefits associated with the gradual reduction of carbon dioxide emissions. Researchers have studied social cost of carbon dioxide ($SCCO_2$) extensively and produced a large number of different estimates (Pearce, 2003) and (Tol, 2007, 2011). According to U.S. government regulations, the newly developed social cost of CO_2 estimate is now used to evaluate the benefits of CO_2 reduction (Marten and Newbold, 2012).

$SCCO_2$ summarizes in principle about the impact of climate change on all relevant market and non-market sectors, such as in water availability, agriculture, human health, biodiversity, energy production, and coastal communities. $SCCO_2$ estimates play an important role in marginal reduction in CO_2 emissions by assessing the benefits of policies (Marten and Newbold, 2012).

Globally, many studies are conducted to evaluate the economic feasibility of energy generation from MSW, using AD and LFG technology. In 2021, Cudjoe and his co-workers conducted a study to assess the economic feasibility of AD and LFG technology to generate electricity from MSW, in 31 provinces of China. Economic feasibility is conducted using economic parameters such as NPV and LCOE. Furthermore, the global warming potential of both technologies are also estimated. Results of the study showed that NPV for Beijing province is 318.9 million USDs and LCOE for Beijing is 0.1413 USD/KWh. Moreover, the study concluded that LFG technology can reduce 71.5% global warming potential and AD technology had potential to reduce 92.7% global warming potential (Cugjoe et al., 2021). In 2016, korai and co-workers conducted another study in Hyderabad, Pakistan, to assess the potential of waste-to-energy in the city using MSW to generate biogas by using anaerobic technology. In this study, they did not perform the economic or environmental analysis for production of biogas from anaerobic technology. Results showed that methane production potential was in the range of 3-22% and heat capacity ranges from 3007 to 20099 kJ/kg. furthermore, they analyze the characteristics of MSW in Hyderabad city of Pakistan (Korai et al., 2016).

Sensitivity analysis is a very common method in assessing the impact of resources on system performance. It is one of the most practical ways for evaluate the performance of the system by varying its inputs. In this technique, the output of the system varies by changing one factor at a time (OAT). This method includes: (1) Changing an input variable while keeping other variables at the nominal value and (2) similarly repeat the process for all other inputs. Sensitivity is determined by monitoring changes in the output of the system, which is a logical method, because any observed output changes are due to changes in moving variables. This practical method is widely appreciated by modelers in different fields (Kermanshachi and Rouhanizadeh, 2019).

Waste-to-energy (WTE) technologies are emerging technologies, especially for the developing nations, to convert waste into energy. Waste-to-energy technology is the most feasible technologies for energy shortage as Pakistan is suffering from energy shortage

(Pakistan economic survey, 2019-20). Currently using the organic part of MSW to generate energy through anaerobic digestion technology is an emerging research topic worldwide. In Pakistan limited studies are currently present to assess the economic feasibility of waste-to-energy technologies but there is no study specific to MSW of Lahore city. Safar and his fellow researchers conducted study in Pakistan to assess different waste-to-energy technologies for energy production, but the main focus of this study is technical aspect. Furthermore, they have estimated total cost and profit of AD and composting technology, while other economic parameter such as NPV, LCOE, IRR and PBP is not evaluated in this study. Moreover, this study is generalized to Pakistan while specific detailed economic analysis for generated MSW of Lahore city for production of electricity is currently not available (Safar et al., 2021). So, the aim of current study is the detailed economic and environmental analysis of electricity generation from MSW of Lahore, using AD and LFG technology with the help of important economic parameters such as TLCC, NPV, IRR and PBP.

1.1. Objectives

This study has following objectives.

1). Estimation of electricity generation from MSW of Lahore, Pakistan.

2). Economic assessment for comparison of AD and LFG technologies, with and without addition of environmental externalities.

3). Analysis of environmental impacts using GWP for AD and LFG technologies.

CHAPTER 2

2. LITERATURE REVIEW

In this chapter extensive literature review is carried out regarding different aspects of the current study. From latest published articles and books, the pre-existing works on anaerobic digestion and landfill gas recovery technologies for production of electricity from municipal solid waste are discussed with special emphasizes on methane generation potential, electricity generation potential in different scenarios, economic viability of both technologies and their environmental impacts. Literature review helped in identifying the research gaps in this field, which are studied in current study.

2.1. Municipal solid waste; generation, impacts, and management.

2.1.1. Municipal solid waste (MSW) generation

MSW normally refers to the solid waste which is generated from commercial, domestic, and industrial sources of pollution, that is managed by municipality authorities. The mismanagement of solid waste is intensified by exponential population growth, urbanization, economic and technological development. Currently, the total municipal waste generation around the world is estimated as 2.01 billion tons per year. It is also estimated that, by 2050 MSW generation per year would be 3.4 billion tons (Kaza et al., 2018).

The factors that influence the waste generation and its composition is socio-economic status of the nations. Developed countries generate large portion of total global municipal solid waste that largely comprises of plastic, paper, and non-organic materials, while the solid waste generated in developing countries have higher concentration of organic materials due to poor solid waste management facilities (Das et al., 2019).

2.1.2. Impacts of mismanagement of MSW

Globally, the mismanagement of MSW contributes to many issues to ecosystem, environment and human health. Inadequate solid waste management practices like open burning, open dumping and unmanaged landfilling contributes to air pollution. Other issues associated with mismanagement of MSW are soil pollution and contamination of water bodies. Exposure to hazardous gasses cause many physical and health problems in human (Kaza et al., 2018). Water contamination due to leachate from unmanaged landfill leads to destruction of aquatic life. According to IPCC, MSW contributes to 3 to 5% of global anthropogenic GHG emissions (IPCC, 2014).

2.1.3. MSW management approaches

In developed countries, proper management of MSW is carried out using different thermal, biological, and physical technologies. Thermal technologies include pyrolysis, incineration, and gasification. On the other hand, the efficient biological technologies are composting, anaerobic digestion, and landfilling with biogas recovery system. This high-end technology requires large investment cost and personal skills, but still they cannot completely neutralize the harmful impacts of MSW, while in developing countries, most common practices for MSW disposal are open dumping, open burning and unmanaged landfilling (Xiong et al., 2019).

2.1.4. Waste-to-energy technologies for MSW

Globally, many technologies are available for efficient management of municipal solid waste. Three main types of waste-to-energy technologies are; biochemical conversion, thermal conversion and landfill technology. The thermal conversion technologies include pyrolysis, incineration, and gasification, while the main biochemical conversion methods are anaerobic digestion through fermentation of organic matter with the help of microorganisms and composting (Tozlu et al., 2016).

A). Thermal conversion of MSW

In this process, biomass is thermally converted into chemical energy. Typical efficiency of thermal biogas plants ranges from 7 to 27%. The outputs of this process are heat, electricity, and fuel for transport. Furthermore, this process reduces the GHG emission and help to reduce climate change phenomenon (Adams et al., 2018). Different thermal conversion processes are described below.

Pyrolysis

Pyrolysis is a process in which materials are thermally decomposed at higher temperature in the absence of oxygen. The main product of the process is char, which is carbon rich solid compound that can be used as fuel. In waste management sector, its advantages include volume reduction of MSW by eliminating water at higher temperatures, pathogen degradation and required external fuel can be avoided by using the gases generated during the process as a fuel source. Disadvantages of the process includes : complex mixture of gases and in product stream, separate unit is required of carbon monoxide from product stream (Nanda et al., 2016).

Incineration

Incineration is the process of burning waste material in the presence of oxygen (oxidation). Higher temperature is required in this process which ranges from 590-650 C. the main advantage of the process is the pathogen removal due to high temperature, and it Is an instant process. Demerits includes: expensive process, hazardous emissions from incinerators and damaging public health (Adams et al., 2018).

Gasification

It is a controlled process that involves heat, stream and O_2 to convert biomass (OFMSW) into hydrogen and other byproducts without combustion. Required temperature is above 700C. this process produce biofuel, syngas, and hydrogen which can be used in energy generation, transportation, and industrial sector. This process has many advantages such as reliability, simplicity, and low-cost process. Furthermore, it is considered as carbon neutral fuel source, so it cancelled out many of the climate change issues by lesser GHGs emission. Disadvantages includes its higher cost and comparison to the other alternatives (Nanda et al., 2016).

b). Bio-chemical conversion technologies

In this process, bio-chemical conversion of biomass takes place under the influence of microorganisms and produce products such as biogas, ethanol, hydrogen, butanol, organic acids etc. in comparison with other biomass conversion techniques, the bio-chemical technologies are clean, pure, moderate and efficient. In addition to this, biomass can also be converted into intermediate useful substances by screening different microorganisms and enzymes (Onoja et al., 2019).

Composting

It is an aerobic process to decompose organic materials. As a result of aerobic decomposition humus like material produces known as compost which can be used as an organic fertilizer in agriculture sector. This process helps in the recycling of organic material. Compost is used in soil nourishment, and it is an eco-friendly technique. Demerits of this process are the unpleasant smell, initial investment and also its efficiency depends on the quality and quantity of the organic waste (Chen et al., 2020).

Figure 2.1 Flow diagram of different technologies for municipal solid waste treatment

2.1.5. Environmental impacts of various waste management technologies

The life cycle assessment technique is used by many researchers to evaluate the environmental impacts of many MSW management technologies (Gear et al., 2018). In a case study of Macau, it is reported that the incineration is most environmentally friendly technology as compared to composting and landfilling (Song et al., 2013).

A study conducted in Nigeria for the comparison between AD and LFG technology on economic and environmental aspects for 20-years period. Researchers estimated the total greenhouse gasses (GHGs) generation potential of both technologies for whole life period of projects. Results of the study confirmed that AD technology is more eco-friendly with total GHGs generation potential of 2770.8 ktons in 20-years period, while LFG technology had higher GHG emission which is 10441.50 ktons in project life period. This shows that LFG technologies had higher adverse impacts on environment as compared to AD technology (Ayodele et al., 2018).

The ecological impact of power generation with biogas plants has also recently been investigated. In 2019, Saracevic and his coworkers conducted study on Austrian biogas power plant and examined the methane emissions caused by biogas-producing facilities at agricultural biogas plants and compared the co-generation of power and heat at biogas plants to fossil fuel-based plants. Results showed that at biogas plant GWP reduces up to 50% as compared to fossil-fuel based plant (Saracevic et al., 2019). Sharma and chandal investigated different bio-conversion methods to identify the best technologies among them in terms of environmental impacts. Results suggest the integrated operation of composting, anaerobic digestion and landfill gas recovery system is found to be most preferable combinations for Mumbai, India (Sharma and Chandel, 2016). Another study reported that AD is best among landfill with gas recovery, gasification, incineration and palletization (Liu et al., 2017).

Previous literature indicates that only the financial benefits of biogas production technologies are estimated. Although in some studies the economic indicators are positive but not in extra-ordinary levels. Environmental benefits are discussed in many studies but there are only few studies which conducted the monetization of externalities for these projects. The incorporation of monetary value of externalities in economic analysis can enhance the worth of these projects (Rasheed et al., 2019).

2.2. Anaerobic digesters

Many developing countries are interested in recovering energy from municipal solid waste. while some European countries have been successful in this regard (Makarichi et al., 2019).

In the countries like Germany, Switzerland, and Denmark, the anaerobic digestion technologies got the success to generate energy from municipal solid waste (Ogunjuyigbe et al., 2017).

The single stage wet digester is used in treatment of municipal; and agricultural of wastewater because of its low solid contents (Rapport et al., 2008). Generally, the CSTR (continuous stirred tank reactor) is prefer for wastewater that contain lower solid content and high volume, while the batch reactors are usually preferred for wastewater whose solid content is high with lower volume (Igoni et al., 2008). Therefore, for the treatment of MSW, the preferred system is the usage of dry-batch reactors, because the organic fraction of MSW have high solid content and low volume Ogunjuyigbe et al. (2017). These findings are supported by previous work conducted by (Igoni et al., 2008). For the treatment of OFMSW, some designed digesters are Varloga, Dranco and Kompogas. Beside this, the multistage digesters have their own benefits such as, they provide more favorable conditions required in different steps of anaerobic biodegradation, especially for substrate that contain low cellulose materials like manure, and poultry waste, but these digesters are expensive and complex to control parameters. Whereas the batch type reactors are easy to handle and have simpler design and less expensive to operate. They have lower operation and capital cost (Nizami, 2012).

Types of anaerobic digesters

2.2.1. Wet digestor

It is low solid, anaerobic system which processes feed stock with less than 15% solid content. Usually, the feedstock is used in slurry form and pumped into digestor. its main advantage is that it allows the optimal mixing of digestor, thus produce higher biogas, investment and operation cost Is lower that than of dry anaerobic digestion process. While it requires costly mixing treatments and highs energy for processing. Furthermore, higher volume of reactor is required for wet anaerobic digestion process which are demerits of wet digestor (Jegede et al., 2019).

2.2.2. Dry digestor

In dry digestors, the feedstock contains higher concentrations of solid contents, usually greater than 15%. Its main advantages include smaller volume of reactor is required because of higher solid content in the given volume of feed stock, it produce fertilizers that can be used in agriculture sectors. The main demerits of dry digestor are: heterogenous distribution of microorganisms and substrate in feedstock, inoculum efficiency reduced due to poor mixing thus less biogas produce as compared to wet digestion process (Jegede et al., 2019).

2.3. Biogas production process

Anaerobic digestion is the engineering behind the biogas production, which is more environmentally friendly process as compared to usage of fossil fuels. In AD, the organic matter is converted into biogas by anaerobic microorganisms in anaerobic conditions, this phenomenon is also termed as decomposition or fermentation. Fermentation process includes four stages shown in Figure 2.2.

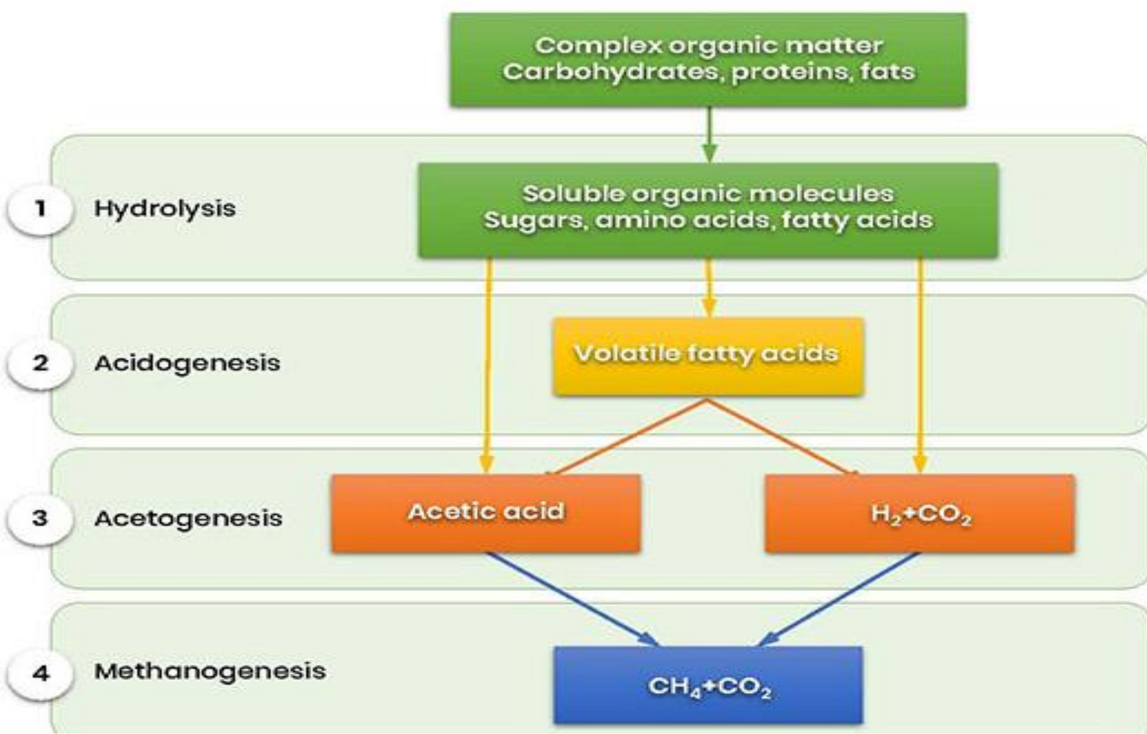

Figure 2.2. Typical biogas production process

In first stage, anaerobic bacteria breakdown carbohydrates. In second stage, the amino acids and sugars are converted into CO_2, organic acids, amino acids, ammonia and hydrogen by acidogenic bacteria. In third and fourth stage, these organic acids are converted into methane and CO_2 by methanogenic bacteria (Sillero et al., 2022). In case of anaerobic digester, the reported methane concentration by volume is 55-70% and for landfill technology its concentration ranges 50-55% by volume. Furthermore, the energy content of methane is about 37.2 MJ/m^3 which make it an important component of biogas and it have a higher potential in generating electricity (Ayodele et al., 2018).

2.4. Electricity generation potential of AD and LFG technology

In 2021, Cudjoe and coworkers conducted a study in different provinces of China to estimate the electricity generation from municipal solid waste using AD and LFG technologies. The electricity generation potential for Beijing province is found to be 77023.7-2532.2 GWh for AD and LFG technology, respectively (Cudjoe et al., 2021).

Aydi and co-researchers used three different models to estimate the landfill gas generation from Jebel Chakr landfill in Tunisia. The authors also estimated the electricity generation potential and environmental impacts of the landfill gas recovery system. Results indicates that electricity generation potential of Jebel chakir landfill is 255 GWh on bigas collection efficiency of 58% (Aydi et al., 2015).

In 2021, De souza and co-workers conducted a study in two states of Brazil to evaluate the electricity generation potential of AD and LFG technologies from MSW of studied areas. In this study algorithms developed by SciLab was used for estimation of electricity generation potential for both technologies. Results of the study indicates that, in case of Sao Paulo state, the electricity generation potential from MSW using AD and LFG technologies are 160 MW and 139.5 MW respectively, while in case of Minas Gerais state, the electricity generation potential through AD and LFG technologies are 17.5 MW and 14MW respectively. These results indicates that in both states, the AD technology had higher potential to generate electricity as compared to LFG technology (De Souza et al., 2021).

Huang and Fooladi have conducted a feasibility study of AD and LFG technology in Tehran and Beijing in 2020, they analyzed the potential of MSW generated in both cities, for the generation of electricity through AD and LFG technologies. Furthermore, they have also conducted economic analysis and GWP analysis of both technologies for given amount of MSW for 20-year period. Their results show that electricity generation potential of AD technology is 45.2% and 41% higher than LFG technology for Tehran and Beijing respectively. Also, the GWP of AD is noted lesser than LFG technology (Huang and Fooladi, 2020).

2.5. Economic analysis of AD and LFG technologies

In 2017, Ogunjuyigbe and co-workers conducted a feasibility study in twelve cities of Nigeria, to evaluate the best waste-to-energy (WTE) technology among the landfill gas to energy (LFGTE), incineration (INC), anaerobic digestion (AD). For economic analysis they used levelized cost of energy (LCOE) and net present value (NPV). Results of the study shows that due to different quality and quantity of municipal solid waste in different cities, the LFGTE and INC are more feasible technologies for northern cities of the country while for the southern cities of Nigeria, the more feasible technology is AD technology (Ogunjuyigbe et al., 2017).

Another feasibility study conducted by T.R Ayodele and his co-researchers for the generation of electricity from MSW of Ibadan city, Nigeria, by using anaerobic digestion technologies. They also analyzed the economic and environmental aspects of this project. They compared the efficiency of anaerobic digestion and landfill gas recovery. Their results indicate that AD using biodigesters are economically more viable and can produce more energy as compared to landfill technologies (Ayodele et al., 2018).

In 2013, Moriarty and his company conducted a feasibility study for anaerobic digestion of food waste in St. Bemard, Louisiana, under the direction of US-EPA. They investigated a site for anaerobic digestion facility and estimated the economic feasibility for this project. Results shows that food quantity is adequate, and the site can support a biomass facility. Furthermore, financial analysis reveals that the project is economically not viable, due to many factors like low area tipping fees and energy prices in that city, as well as the high capital cost of the project (Moriarhy, 2013).

In 2018, Octavianthy and his co-researchers conducted a feasibility study to design the smart energy system by using waste-to-energy technology in Depok, Indonesia, to assess its economic viability. The technology under analysis was the anaerobic digestion and gas engine to generate electricity. They used software like SuperPro designer and Unisim designer, to evaluate the technical performance of project. Furthermore, they designed different business models to attract investors for this waste-to-energy project. They found that the organic friction of MSW of Depok city have the potential to generate up to 28MW electricity. Related to business schemes, they reported that the combination of "increasing tipping fees intervention scheme" and viability GaP fund (VGF) scheme is an optimum business scheme that will produce electricity below the existing prices (Octavianthy and Purwanto, 2018).

In 2019, Nina Tsydenova and co-researchers conducted a study related to feasibility and barriers of anaerobic digestion in Mexico. They used cost benefit analysis (CBA), net present value, internal rate of return, and payback period to evaluate economic feasibility. Furthermore, they also conducted environmental impact assessment of project. Results show that net present value was positive and payback period was 7 years. Environmental impacts were also positive i.e., 730 kg CO2 per 1Mg of MSW. They also found some barriers to use MSW to generate biogas including the need of large investment, low profitability through sales of electricity, no use of generated heat that goes out of system. They provided some recommendations like the use of other by-products of anaerobic digestion process like the excess heat and digestate, to make the project more profitable (Tsydenova et al., 2019).

2.6. Importance of sensitivity analysis

Sensitivity analysis helps to understand the output of a system in according to different inputs. In 2018, Ayodele and co-workers conducted economic analysis of AD and LFG technologies to generate electricity from MSW. Furthermore, sensitivity analysis was also conducted on different electricity generation efficiency against economic indicators.

Results of the study showed that by increasing electricity generation efficiency from 20-40 %, the LCOE reduced to 0.040- 0.073 USD/kWh and 0.049- 0.070 USD/kWh for AD and LFG technology, respectively. NPV increased from 390-1000 million USD and 225-600 million USD in case of AD and LFG technology respectively (Ayodele et al., 2018).

2.7. Waste management profile of study area

In Pakistan there is no proper system for MSW management. Only 60% waste is collected and dumped in open solid waste dumping sites. Furthermore, there is no engineered landfill in Pakistan nor any waste-to-energy treatment facility in bigger level for any town or city (Korai et al., 2020).

The population of Lahore city is 8.16 million (2017) and it covers the area of 1772 km2. About 5500 tons of solid waste is collected per day from the city. Lahore has nine administrative towns, these towns are further divided into 274 union councils (Azam et al., 2020). In 2010, Lahore waste management company (LWMC) is established for the improvement of solid waste management services in the city. In 2012, LWMC signed a contract to privatize the solid waste management of city with two Turkish companies Albayrak and OzPak. Lahore city is administratively divided into two zones. Responsibility of zone A is given to Albayrak, and zone B is assigned to OzPak (LWMC, 2012). These companies have the responsibility to collect, transport and dispose the waste of the city.

In Lahore, these is no scientifically engineered landfill in operational conditions. Before 2016, the official waste dumping site in the city was Mehmood booti dumping site, while two others unofficial publicly administrated dumping site i.e., Sagian and Bagarian were also in use. In 2016, after the closure of Mehmood booti dumping site, the Lakhodair dumping site is official dumping site for collected waste of Lahore city. Furthermore, these companies have not any agreement regarding the segregation of solid waste, rather they only collect the waste and dump it into dumping sites (Mohsin et al., 2020) (khalil et al., 2019).

Table 2.9 Types of anaerobic digesters

Classification basis	Digester types
Substrate feeding	Batch and continuous digesters
Operating temperature	Mesophilic (25-40 °C), thermophilic (50-65 °C) and psychrophilic (10-15 °C) digesters
Substrate Solid contents	Dry and wet digesters
Substrate type	High solids (>20 %TS) and low solids (<20% TS) digesters
AD process complexity	Single stage and multistage digesters
Scale of digester	Farm-based, food processing and centralized digesters

Table 2.10 Differences between AD and LFG technologies (Ouda et al., 2016)

AD	LFG
Takes place in a digester	Takes place in a sanitary landfill
Less space is required	Large space is required
Digestate of AD technology can be used as organic fertilizers.	Leachate from LF can contaminate water resources.
Requires space for storing feedstock	Storage of waste is not required, it can be dump in landfill directly.
Cost effective but more expensive	Less expensive
GHG Minimization	If not collected large GHG is emitted
Methane content in biogas is 50 to 70%.	Methane content in biogas is 50-55%
Biogas is collected from biogas valve.	Biogas collection wells are required

CHAPTER 3

3. MATERIALS AND METHODS

In this chapter, complete methodology is presented which is used in current study. In current chapter, step wise methodology is given for each part of the study which are the estimation of total MSW generation projection of 20-years for study area, methane generation potential from AD and LFG technology, electricity generation from biogas of both technologies, economic and environmental assessment of AD and LFG technology for the sake of comparison, and sensitivity analysis of AD technology. The flow diagram of complete methodology for current study is shown in Figure 3.1.

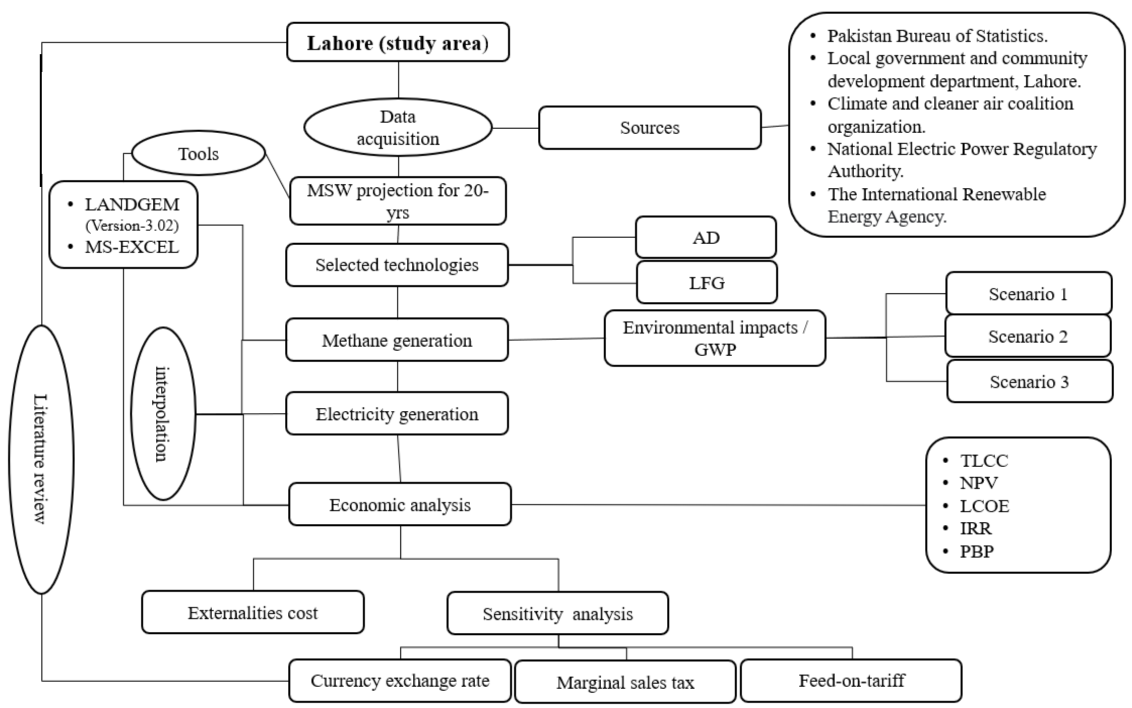

Figure 3.1. Flow diagram of complete methodology used in this study

3.1. Study area

Lahore is selected as study area for this study. It is situated at latitude of 31.58 N while the longitude is 74.32 E. It is second largest city of Pakistan. The population of Lahore city is 12.81 million and it covers the area of 1772 km^2. About 7690 tons of solid waste is generated per day from the city. Currently the Lahore waste management company

(LWMC) is responsible for the management of municipal solid waste of this city. Satellite map of study area are shown in Figure 3.2.

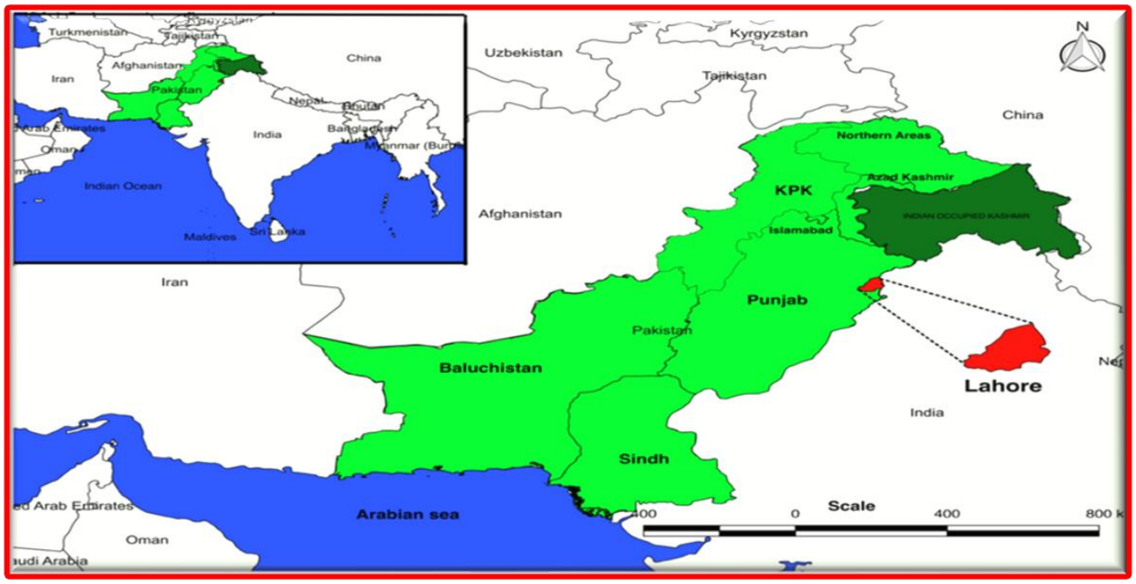

Figure 3.3 Satellite map of Lahore city

3.2. Total MSW generation from Lahore city

The quantity of MSW generated in any area, depends upon the population and income of inhabitants. Higher population of any area and higher economic status contributes in the increase of total MSW and vice versa. So, the amount of total MSW (tons/year) generation projection for given period of any area can be calculated using following equations.

$$MW_G(t) = \frac{(P_{OP}(t) \times W_{GR}(t) \times 365)}{1000} \frac{tons}{yr} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Here:

$MW_G(t)$ = Projected total waste generation in ton/year

$P_{OP}(t)$ = Estimated population projection over a period of time

$W_{GR}(t)$ = Per capita waste generation rate (kg/capita/day)

t = The number of years

$$P_{OP}(t) = P_{OP_{base}} \times (1 + r_{pop})^t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

r_{pop} = population growth rate

$P_{OP_{base}}$ = initial population

$$W_{GR}(t) = W_{GR_{base}} \times (1 + q)^t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

$W_{GR_{base}}$ = Per capita waste generation rate

q = Growth rate in waste generation (GDP growth rate)

The waste generation per capita increases with economic growth of any country in terms of GDP. The waste generation rate in any area depends on level of income which corresponds to economic growth rate. So, the value of "q" in equation 3 would be the value of average GDP growth rate of given area.

Table 3.11. Parameters to calculate total MSW generates in Lahore city

Sr. no.	Parameters	Values
1	r_{pop} (%)	3.73[a]
2	q (%) (Avg. GDP)	3.76[a]
3	$W_{GR_{base}}$ (kg/capita/day)	0.65[b]
4	D_F (%)	95[c, d]
5	$f_{(LFG)}$ (%)	79.17[b]
6	$f_{(AD)}$ (%)	56[b]
7	$P_{OP_{base}}$ (2021)	12881537[a]

a (PBS, 2017), b (Azam et al., 2020), c (LGCD, 2021), d (CCACO, 2021)

All the generated municipal solid waste is not dumped in landfills. A smaller fraction of this waste is deposited in unauthorized places. Different cities have different waste collection efficiencies depending upon waste collection authorities. As, the collection efficiency of MSW in Lahore city is 95% by Lahore waste management company (LGCD, 2021); (CCACO, 2021). Hence, the quantity of collectable waste MW_C (tons/year) in Lahore can be evaluated using following equation.

$$MW_C \text{ (tons/year)} = D_F \times MW_G(t)$$

Here, $MW_G(t)$ represents the mass of total MSW generated in each year and is obtained from equation 1. D_F is the fraction of MSW that is collectable and deposited in the landfill. For maximum energy recovery, the selected components of MSW should be used for both technologies. In this study, the biodegradable organic fraction (food waste) of MSW is used in AD technology. Other organic components such as wood, which is avoided because of its high lignin content. On the other hand, in case of LFG technology, all the MSW is used except inert and recyclable materials (glass, metals, plastic and paper) which are

20.83% as shown in Figure 3.2. The fraction of MSW (tons/year) that would be used in AD and LFG technology for the generation of electricity can be calculated by using following equation.

$$MW_{OF(i)}(t) = MW_c(t) \times f\,(i)\ (\text{tons/year})$$

Where f is the fraction of the MSW that can be used in AD and LFG technology. i is the type of technology that would be AD or LFG technology, while t represents the year of calculation.

3.3. Determination of methane generation from AD technology

The Varloga single stage dry-batch digester is proposed in this study. This is because of its mature design and commercial availability. Furthermore, this technology is currently used world widely (Amoo and Fagbenle, 2013). This digester need mesophilic condition for better function and the average annual temperature of study area (Lahore) is 24.0 °C (Nasar-u-Minallah & Ghaffar, 2020).

The internal combustion engine (ICE) or combined heat and power plant (CHP) can be used to produce electricity from the generated biogas. However, the biogas must be purified before consumption. So, the biogas purification process is carried out to increase the methane concentration in generated biogas to fulfil specified natural gas standards (Rajaeifer et al., 2017). After further treatment the digestate can be used as organic fertilizer. However, in current study only electricity generation potential is focused.

To estimate the potential of AD technology to generate electricity, the amount of methane that can be produced through AD digester using given amount of feedstock must be determined. The potential of organic fraction of MSW to generate methane (m^3/year) can be calculated using Bush-well’s equation (Amoo and Fagbenle, 2013). This is stoichiometric equation that is based on biodegradation of organic waste according to its elemental composition which is given below:

$$C_wH_aO_bN_c + \left(w - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right) H_2O ==> \left(\frac{w}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) CO_2 + \left(\frac{w}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 + cNH_3 \text{ ---------------- } (4)$$

Here w, a, b, and c are constants, and their values are determined by the normalized mole ratio suggested by (Salami et al., 2011). Normalized mole ratio can be found as under:

$$\text{Mole ratio} = \frac{K(C, H, O, N)}{M(C, H, O, N)}$$

Here, K represents the elemental composition of carbon, hydrogen, oxygen, and nitrogen. k is obtained from ultimate analysis of organic fraction of municipal solid waste (OFMSW) of Lahore city conducted by (Azam et al., 2020), M represents the molar-mass of the element, shown in Table 3.4. So, the obtained chemical formula of MSW without Sulphur is $C_{262.14}H_{372.52}O_{101.67}N$.

The specific theoretical methane S_{CH_4} yield in (Nm^3CH_4 /ton) at standard pressure and temperature (1 atm at 0 °C) are obtained as (Nielfa et al., 2015).

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

Practically, the actual yield of methane is lesser than the theoretical yield of methane. This is because, about 10% of OFMSW doesn't degrade in anaerobic digester. Furthermore, about 5-10% of OFMSW is utilize by microorganisms for the synthesis of their cell tissues (Nizami, 2012b). so, the actual yield of methane in m^3 can be calculated as:

$$CH_4 = F_C \times MW_{OF}(AD) \times S_{CH_4}$$

Here, F_C represents the fraction of organic waste utilize by microorganisms for their cell tissues synthesis while $MW_{OF}(AD)$ represents the annual feedstock fed in AD technology.

Table 3.12. Composition of MSW in Lahore city (Azam et al., 2020)

Sr. NO.	**Waste type**	**Waste composition (%)**
1	Biodegradable	56.32
2	Nylon/Plastic	11.55
3	Noncombustible /Inert	6.4
4	Textile	9.21
5	Paper	2.18
6	Wood	6.05
7	Diapers	5.06
8	Glass	0.69
9	Metal	0.06
10	Others	2.48

Table 13.3. The ultimate analysis of municipal solid waste of Lahore city (Azam et al., 2020)

Waste components	% C	%N	%H	%O	%S	%Ash	%Moisture
Biodegradable	62.5	0.4	8.0	28.8	0.1	9.6	4.0
Textile	58.4	0.6	4.9	35.7	0.16	5.0	2.9
Nylon plastic bags	78.7	0.12	12.4	8.7	0.02	5.5	0.1
Paper	50.5	0.22	6.4	42.3	0.55	18.8	3.4
Pet bottles	62.0	0.05	4.1	34	0.01	0.2	ND
Average	**62.42**	**0.278**	**7.16**	**29.9**	**0.168**	**7.76**	**2.6**

Table 3.4. The normalize mole ratio. by (Salami et al., 2011)

Element	Mass (kg)	kg/mole	Moles	Mole ratios Nitrogen = 1
Carbon	62.42	12.01	5.197	262.14
Hydrogen	7.45	1.01	7.376	372.52
Oxygen	32.21	16.00	2.013	101.67
Nitrogen	0.278	14.01	0.0198	1.00

3.4. Determination of methane (CH_4) generation potential of LFG technology

In this study, the potential of LFG technology to generate methane in meter cube is determined by using landGem model (version 3.02), which is developed by United States Environmental protection agency (US-EPA, 2005).

In current study, the methane generation potential of conventional landfill is estimated using LandGem model (version 3.02), which is developed by US environmental protection agency (USEPA, 2005).

$$CH_{4(LFG)} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} KL_O \left(\frac{MW_{c(LFG)}}{10}\right) e^{-Kt_{ij}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 5$$

Here,

$CH_{4(LFG)}$ =Annual flow rate of methane from landfill (m^3/year)

n = Difference between the year of calculation and initial year of waste acceptance

i = The 1-year increment

j = The 0.1-year time increment

k = Per year methane generation rate

L_O = Methane generation capacity (m^3/year)

$MW_{c(LFG)}$ = The amount of MSW assumed to be landfilled

t_{ij} = The age of j^{th} section of waste in year "i"

K = The methane generation constant per year

The L_O and K are important parameters used in landGem model which can be calculated according to (Ogunjuyigbe et al., 2017). The inputs for this model are "K", "L_O", time-period in years and amount of waste that goes to landfill ($MW_{c(LFG)}$), which would be used in equation 5 using landGem model.

Calculation of parameters to find out the amount of methane from MSW of Lahore, using LandGem model (version 3.02) are as under.

3.4.1. Potential methane generation capacity (L_O)

Potential methane generation capacity (L_O) is the factor which determines the potential of landfilled solid waste to generate specific quantity of CH_4 from a unit mass of waste in its life span in landfill. L_O depends upon the nature of landfilled waste.

For the waste which contain a lot of cellulose, will have higher L_O value. Its value can be calculated as follow:

$$L_o = DOC \times DOC_F \times MCF \times F \times 16/12 \quad \text{……………………………………} \; 6$$

Where:

MCF = The correction factor for CH_4

F = The fraction of CH_4 in the biogas

DOC_F = The assimilated fraction of degradable organic carbon

16/12 = Factor used for Conversion of C to CH_4

DOC = The degradable organic carbon

The values of parameters used in equation 6 can be calculated as under:

Table 3.5. Amount of waste goes to land fill each year (ton/year)

Years	MW_G (t) ton/yr	D_F	$F_{(LFG)}$	MW_F (ton/yr)
2021	3289336.12	0.95	0.7917	2473959.034
2022	3540320.62	0.95	0.7917	2662728.244
2023	3810455.86	0.95	0.7917	2865901.013
2024	4101203.10	0.95	0.7917	3084576.367
2025	4414135.06	0.95	0.7917	3319937.194
2026	4750944.52	0.95	0.7917	3573256.635
2027	5113453.37	0.95	0.7917	3845904.978
2028	5503622.54	0.95	0.7917	4139357.066
2029	5923562.59	0.95	0.7917	4455200.276
2030	6375545.10	0.95	0.7917	4795143.106
2031	6862015.01	0.95	0.7917	5161024.417
2032	7385603.77	0.95	0.7917	5554823.379
2033	7949143.65	0.95	0.7917	5978670.179
2034	8555683.03	0.95	0.7917	6434857.541
2035	9208502.86	0.95	0.7917	6925853.129
2036	9911134.47	0.95	0.7917	7454312.899
2037	10667378.61	0.95	0.7917	8023095.46
2038	11481326.05	0.95	0.7917	8635277.541
2039	12357379.70	0.95	0.7917	9294170.633
2040	13300278.42	0.95	0.7917	10003338.9

3.4.2. Degradable organic carbon (DOC)

According to IPCC, following equation can be used to calculate DOC.

$$DOC = 0.4 \times (A) + 0.17 \times (B) + 0.15 \times (C) + 0.3 \times (D) \quad .... 7$$

Where:

A = The fraction of cardboard, paper, and textile

B =non-food putrescibles / gardens and park waste

C = fraction of food waste

D = the fraction of wood/ straw

Figure 3.3 shows the values of degradable organic carbon related to A, B, C, and D. By putting value in equation 7, we get.

$$\mathrm{DOC} = 0.4 \times (11.39\%) + 0.17 \times (15.0\ \%) + 0.15 \times (56.32\%) + 0.3 \times (6.05\%) = 0.173\ \mathrm{M_g/M_g\ MSW} \ldots\ldots\ldots\ldots 8$$

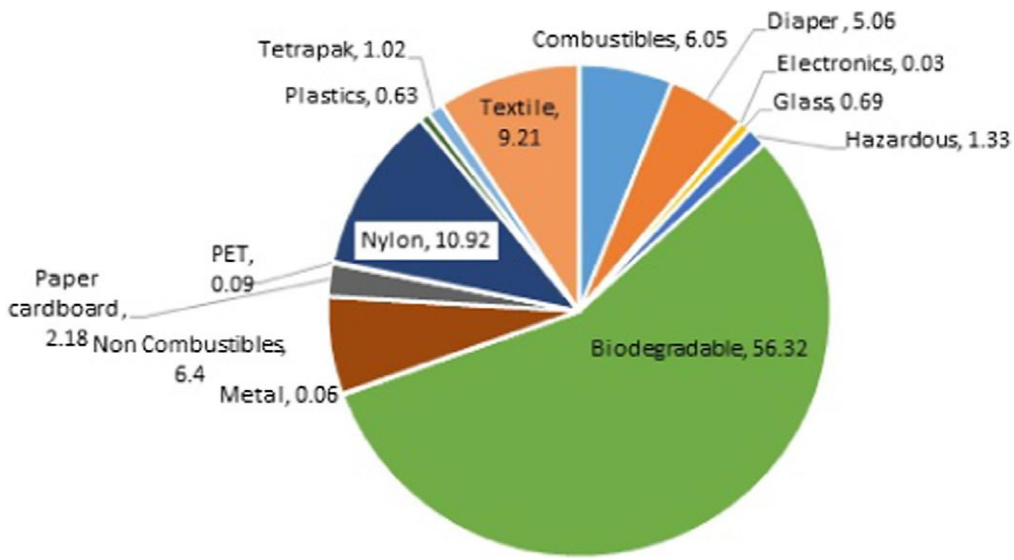

Figure 3.3. Physical percentage composition of the MSW for the calculation of degradable organic carbon (Azam et al., 2020)

3.4.3. Assimilated fraction degradable organic carbon (DOC_F)

DOC_F is the assimilated fraction of degradable organic carbon. This factor is based on theoretical model and variation in temperature of landfill can change its value. It can be estimated using following equation (US-EPA, 2005).

$$\mathrm{DOC_F} = 0.014 \times \mathrm{T} + 0.28 \ldots\ldots\ldots\ldots 9$$

Here, T represents annual average temperature of study area (Lahore). The average annual temperature in the study area is 24.0 °C (Nasar-u-Minallah and Ghaffar, 2020). By putting its value in Equation 9 we get:

$$\mathrm{DOC_F} = 0.014 \times 24.0 + 0.28 = 0.616\ \mathrm{MgC/\ MgC} \ldots\ldots\ldots 10$$

3.4.4. Fraction of CH_4 in LFG (F)

According to literature the range of methane concentration in biogas ranges from 50 to 60%, while the default value in the IPCC Guidelines is 55%. It is assumed as 0.55 for methane in this study.

3.4.5. Methane correction factor (MCF)

This factor is an adjustment to the estimated methane generation in the model that considers the degree of anaerobic degradation of landfilled waste. MCF mainly depends upon the type of landfill and its depth. It is assumed that the methane yield of unmanaged landfill is less than the managed one. Waste present at the top of landfill undergoes aerobic digestion so the MCF of landfill varies with management techniques and site conditions (Kumar et al., 2004).

The MCF for different category of landfills is shown in Table 3.6 (Aguilar-Virgen et al., 2014). Since the landfill in this study would be less managed and depth above 5 meters, the MCF is assumed as 0.8.

Table 3.6. Default values of MCF for different landfills

Management type	Depth < 5 m	Depth > 5 m
Without management	0.4	0.8
With management	0.8	1.0
Semi-aerobic	0.4	0.5
Condition unknown	0.4	0.8

Potential methane generation capacity (L_O) can be estimation by putting values of different inputs in equation 6.

$$L_0 = 0.173\,\frac{\text{Mg C}}{\text{Mg MSW}} \times 0.616\,\frac{\text{Mg C decomp}}{\text{Mg C}} \times 0.8 \times 0.55 \times \frac{16}{12}.\frac{\text{g/mol}}{\text{g/mol}}$$

$$L_0 = 0.0625\,\frac{\text{Mg CH}_4}{\text{Mg MSW}}$$

The density of methane at STP is 0.714 kg/m^3. So, the mass of methane per mass of waste can be calculated as a volume per mass of waste.

$$L_0 = \frac{0.0625 \times 1000}{0.714} = 87.54\ \text{m}^3/\text{Mg}$$

3.4.6. Methane generation constant (K)

K is the factor that defines time span of methane generation from a waste stream under specific site conditions. Organic fraction of MSW is primarily composed of lignin, cellulose, hemicelluloses, and protein. These components (except for lignin) are also the main components converted to methane through biological, chemical, physical processes. Temperature, pH and moisture content also had vital role in biodegradation of waste in landfill (Reinhart & Barlaz, 2010). In literature, the range of methane generation constant (K) is from 0.01 to 0.21 year^{-1}. But in specific condition, K value is reported higher which is 0.3 and 0.5 year^{-1} (Faour et al., 2007). Site-specific values can be calculated using the Equation 11.

$$k = 3.2 \times 10^{-5} \text{ (annual mean rain fall, mm)} + 0.01 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 11$$

In study area the average annual rainfall is 628.6 mm (244.8 in) (Siddiqui and Siddiqui, 2019). By using this value in equation 11, we get:

$$k = 3.2 \times 10^{-5} (629) + 0.01 = 0.030 \text{ year}^{-1}$$

By using the calculated values of K and L_O in LandGem model, methane generation potential from land fill can be estimated.

3.5. Electricity generation potential of AD and LFG technology

The potential of AD technology to generated electricity $E_{P(AD)}$ and the electricity generation potential of LFG technology $E_{P(LFG)}$ (kWh/year) can be determined using following equations (Ayodele et al., 2018).

$$E_{P(AD)} = \frac{(CH_{4(AD)} \times E_{ff} \times LHV_{CH_4} \times CF)}{3600000} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 12$$

$$E_{P(LFGR)} = \frac{(CH_{4(LFG)} \times E_{ff} \times LHV_{CH_4} \times \lambda \times (1 - f_{ox}) \times CF)}{3600000} \quad \ldots\ldots\ldots\ldots \quad 13$$

Here:

$CH_{4(AD)}$ = Volume of methane generates from AD technology

$CH_{4(LFG)}$ = Flow rate of generated methane from landfill

E_{ff} = Efficiency of engine to generate electricity

LHV_{CH_4} = Lower heating value of methane

λ = Landfill gas (methane) collection efficiency

f_{ox} = Oxidation factor in landfill

CF = Capacity factor of the plant

Capacity factor (CF) is the ratio between processed waste in each year and the waste that could be processed if the plant works at its maximum capacity (Hadidi and Omer, 2017). To determine the energy generation in GWh from AD and LFG technology, Equation 12 and 13 are used. The values of parameters for these equations are given in Table 3.7. To covert MJ/year into GWh, divide the value in MJ/year with $10^{6.}$

Table 3.7. Parameters for estimation of methane generation and electricity production from AD and LFG technology

Sr. no	Parameter	Value
1	CF (%)	85[a]
2	E_{ff} (%)	35[b]
3	LHV-CH_4 (MJ/m^3)	37.2[c]
4	f_{0x} (%)	10[d]
5	λ (%)	75[e]

a = Salami et al. (2011)

b = Hadidi and Omer. (2016)

c = Chowdhury et al. (2020)

d = IPCC. (2006)

e = (Amini et al. (2013)

Globally, the internal combustion engines are used to generate electricity from methane, obtained from AD and LFG technology. For mega level projects that produce more than three megawatts of electricity, the multiple engines are essential (LMOP, 2015). In determination of size (capacity) of plant for AD and LFG technology, it is assumed that the plant would be functional throughout the year i.e., 8760 hours. So, the size of plant (P_S) for both technologies can be calculated using following equation.

$$P_{S(i)} = \frac{E_P(i)}{8760} \quad \text{.............................} \; 14$$

Where, i is type of technology which could be AD or LFG technology, E_p is the amount of electricity produced from either technology.

3.6. Economic assessment of AD and LFG technologies

In this study, some important economic parameters are calculated for both AD and LFG technology to assess the economic viability of these technologies. The economic parameters such as TLCC, LCOE, NPV, IRR and PBP are used in current study to evaluate the economic viability of both AD and LFG technologies.

3.6.1. Total life cycle cost (TLCC)

TLCC is a vital financial indicator to assess the economic viability of a project. It consists of the investment, operation, and maintenance cost of a project over its life period (Ayodele and Ogunjuyigbe, 2015). Furthermore, in this study, it is assumed that the waste of whole city is collected in single point and waste collection cost is not includes in the study. TLCC is the sum of investment cost (C_{inv}) and the operation and maintenance cost ($C_{O\&M}$). TLCC of the projects can be calculated using following equation.

$$\text{TLCC}_{(I)} = C_{inv(i)} + \sum_{n=1}^{N} \frac{C_{O\&M}}{(1+0.1)^n}$$

Where, $C_{O\&M}$ is operation and maintenance cost of a project. The $C_{O\&M}$ can be calculated as under.

$$C_{O\&M(i)} = F_{O\&M(i)} + V_{O\&M(i)}$$

Here, $F_{O\&M}$ is the fixed operational and maintenance cost, while the $V_{O\&M}$ variable operational and maintenance cost that includes the cost of broken equipment replacements, unscheduled maintenance, and residue disposal from digester, while the $F_{O\&M}$ is the cost of routine operation and maintenance that are required to run a unit. i is the type of technology that could be AD or LFG technology.

Cost of investment, operation and maintenance for anaerobic digestion technology

The investment cost (C_{inv}) of AD technology can be calculated as under (Hadidi and Omer, 2017).

$$C_{inv(AD)}(\text{USD}) = C_{pu}(\text{USD/kW}) \times P_{s(AD)}(\text{kW})$$

Here, C_{pu} refers to plant specific cost of anaerobic digestion technology, which is 4339 USD/kW (IRENA, 2012). The $P_{s(AD)}$ is the required size of digester in kW, calculated using equation 14. The operation and maintenance cost of AD technology can be calculated using following equation.

$$C_{O\&M(AD)} = 0.03C_{inv(AD)} + 0.005E_{p(AD)}$$

Here, the value of $F_{O\&M}$ is assumed 3% of capital cost according to literature (Hadidi and Omer, 2017). The $V_{O\&M}$ depends upon the plant's output. So, it is expressed as per unit value of plant's output. Its value is taken as 0.5% of the electricity produced in kWh from AD technology (Hadidi and Omer, 2017).

Cost of investment, operation and maintenance for LFG technology

For landfill gas recovery technology, the initial investment cost can be calculated as.

$$C_{inv\ (LFGR)} = \sum_{k=1}^{n5} Ci_k$$

Where, Ci_k represents the different types of investment cost, which can be calculated using following equations (US, EPA, 2016).

$$Ci_1 = \$85 \times N \times (Dwell - 10(ft))$$

$$Ci_2 = N \times \$17000$$

$$Ci_3 = (CH_{4LFG})0.6 \times \$4600$$

$$Ci_4 = N \times \$700$$

$$Ci_5 = (\$1300 \times P_{S(LFGR)} + \$1100000$$

Here, Ci_1 is the cost to install the vertical gas extraction wells. Ci_2 represents the cost of pipe networks and wellheads. Ci_3 represents the capital cost to install blower, knockout, and flare system. Ci_4 is the cost of surveying, planning, permitting, and engineering for landfill. Ci_5 is the cost of landfill gas recovery facility installation.

Furthermore, D_{well} represents the depth/height of wells which is taken 65.6 ft, according to previous studies (Feng et al., 2018). $CH_{4\ LFG}$ is the flowrate of methane in (ft^3/day), "N" shows the number of wells required for landfill site calculated in annex 1. $P_{S(LFGR)}$ is the size of LFG plant which can be calculated using equation 14. The $C_{O\&M}$ of landfill gas recovery technology can be estimated as:

$$C_{O\&M(LFG)} = C_{O\&M(LF)} + C_{O\&M(plant)}$$

The $C_{O\&M(LF)}$ is the cost required to operate and maintain the landfill site, while the $C_{O\&M(plant)}$ represents the operation and maintenance cost of LFG plants. $C_{O\&M(LF)}$ and $C_{O\&M(plant)}$ can be estimated as.

$$C_{O\&M(LF)} = \$2600 \times N + \$5100$$

$$C_{O\&M(LFGR)} = \$0.025 \times E_{P(LFGR)}$$

where, $E_{P(LFGR)}$ is the amount of electricity in (kWh) produced annually by LFG technology.

3.6.2. Levelized cost of energy (LCOE)

LCOE refers to the minimum cost to generate electricity in USD/kW by a system (Ogunjuyigbe et al., 2017). It is a vital economic indicator to compare different technologies in terms of cost, to produce one unit of electricity. TLCC for AD and LFG technology can be estimated using following equation (NREL, 2011).

$$LCOE_{(I)} = \left(\frac{TLCC_{(i)}}{Ep\ (i)}\right)$$

Here, TLCC refers to the life cycle cost of the project, i is the type of technology.

3.6.3. Net present value (NPV)

NPV is the difference between the present value (PV) of all the expenses used for a project in its life period and the present value (PV) of all the revenue earned from the project in its life period. Simply, it is the difference between cash inflows and cash outflows.

Cash outflows refers to the cost which is spend on a project in terms of its investment, operation, and maintenance cost, while cast inflows are the financial benefits obtained from a project. Any project will be economically viable if its NPV is greater than 1 (NREL, 2011). NPV can be calculated by following equation.

$$NPV_{(I)} = \sum_{n=1}^{N} \frac{F_n}{(1+d_r)^n} - F_o$$

Here, F_n are the net cash flows, N is the total numbers of years of the project, d_r represents the annual real discount rate. F_o is the initial investment cost i.e., C_{inv} for given technology. F_n and d_r can be calculated as:

$$F_n = R_{ev}(i) + \text{Ben}(i) - (C_{O\&M(i)} + C_{Tax}(i))$$

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

Where, d_n is nominal discount rate, e_{inf} is the inflation rate, R_{ev} represents the revenue gained from the project, Ben are the extra benefits obtained from the project (i.e., the cost of externalities). $C_{O\&M}$ is the cost of operation and maintenance, while C_{Tax} is the tax paid on profit of the project. The factors required to calculate cashflows F_n can be calculated using following equations.

$$R_{ev}(i) = E_P(i) \times F_d$$

$$P_{r\,(i)} = R_{ev}(i) - C_{O\&M(i)}$$

$$C_{Tax}(i) = Pr(i) \times T_{rate}$$

Where, E_P is the amount of electricity generated from the system, F_d is the feed-in-tariff or the cost at which electricity is sales out in (USD/KW), P_r refers to the profit on investment, i is the type of technology, T_{rate} is the marginal tax rate. Fortunately, MS-EXCEL has the function of NPV, so all these calculations are conducted using MS-EXCEL.

3.6.4. Internal rate of return (IRR)

IRR is a discount rate which makes the NPV of all cash flows equals to zero in a discounted cashflow analysis. If the IRR value is greater than zero then the project would be economically viable (NREL, 2011). In current study, MS-EXCEL is used to calculate IRR from discounted cash flows.

$$NPV_{(I)} = \sum_{n=0}^{N} \frac{F_n}{(1+IRR)^n} = 0$$

Here, F_n represents the cash flows and N represents the life span of project in years.

3.6.5. Payback period (PBP)

PBP is the length of time (in years) required to recover the capital cost of a project. It is the maximum time after which the project starts the returns on investment. PBP can be calculated as.

$$PBP\ (i) = \frac{TLCC\ (i)\ (USD)}{C_{saved}(i)(USD/year)}$$

Here, C_{saved} represents the cost saved, (TLCC) is the life cycle cost, (i) represents the type of technology which could be AD and LFG technology. C_{saved} can be estimated using following equation.

$$C_{saved}(i) = R_{ev}(i) - C_{O\&M(i)}$$

Where, R_{ev} represents the revenue gained from the project, ($C_{O\&M}$) is the cost of operation and maintenance. The parameters used to estimate the economic potential of both the AD and the LFG technologies are depicted in Table 3.8.

Table 3.8. Parameters used in economic analysis of AD and LFG technologies

Sr. no	Indices	Value
1	$e_{inf}(\%)$	7.356[a]
2	$d_n(\%)$	10[b]
3	$T_{rate}(\%)$	29[c]
4	$F_d\ (\frac{USD}{kWh})$	0.0645[d] (PKR 10.3170)
5	$C_{pu}(\frac{USD}{kWh})$	4339[e]

a = Statista. (2020)

b = CEIC. (2020); Tahir. (2020)

c = Nazir et al. (2020)

d = NEPRA. (2021)

e = IRENA. (2012)

3.7. Environmental assessment by life cycle assessment (LCA)

LCA has been a vital tool in evaluation of inputs, outputs and the potential environmental impacts of any project, process, or service during the whole life span. This tool is applicable in different systems and processes like waste management systems, waste disposal and treatment systems and recycling processes (Kulczycka et al., 2015).

3.7.1. GWP assessment of AD and LFG technology

In current study, the AD and LFG technology is used to generate bigas which is the main product of these processes. Therefore, the methane leakages from both technologies are calculated to evaluate its impacts on environment. For all inputs, zero burdens are assumed which are used in LCA in this study. This indicates that all environmental impacts cause during manufacturing of products prior to becoming a waste are neglected. The functional unit of this study is tons of MSW treated in the selected location between 2021 and 2040. The emissions of GHGs are considered and their global warming potential is used to evaluate the impacts on environment from AD and LFG technology. Although, the GHGs comprises of methane, carbon dioxide, nitrous oxide, perfluorocarbons, sulfur hexafluoride and hydrofluorocarbons. However, only methane is used to evaluate GWP in this study. Following three scenarios are considered in current study, to calculate GWP of AD and LFG technology for environmental assessment.

3.7.1.1. First Scenario (business as usual)

In first scenario all the municipal solid waste (except inert and recyclable materials) are disposed in landfills without energy recovery system.

Methane and carbon dioxide are released when the MSW is disposed in landfill, due to biodegradation of organic components of MSW that leads to global warming. The GWP of methane is 25 times higher as compared to carbon dioxide (Ryu, 2010). It was found from the literature that the amount of CO_2 released from the biodegradable part of MSW are same as the amount of CO_2 absorbed during its life period (Ayodele et al., 2017). Therefore, only methane is considered in this scenario. Methane is the main component of biogas, and it is a strong greenhouse gas. The methane must be converted into CO_2-equalent to analyze its GWP, because carbon dioxide is most significant GHG that comprises because carbon dioxide is most significant GHG that comprises 77% of global GHGs emissions (Adeoti et al., 2014). According to first scenario, 90% of capturable methane from landfill is released into atmosphere (Eggleston et al., 2006) and the rest is oxidized directly to $CO_{2.}$ The following equation describes the methane emissions (in tons/year) for the first scenario:

$$\mathrm{M_{(LFGR)}(ton/year) = \ Q_{CH4(LFG)}(t) \times (1 - f_{ox}) \times 0.00667}$$

Here, 0.000667 is the conversion factor for methane from m^3/year to tons/year. f_{ox} is the oxidation factor which is 10% according to IPCC. This 10% methane is oxidized into CO_2 due to soil cover near landfill surface. The CO_2 produced due to oxidation of methane is biogenic origin, so it is assumed as carbon neutral. The methane equivalent of carbon-dioxide ($M_{CO_{2eq}(LF)}$) is obtained from following equation.

$$M_{CO_{2eq}(LF)} = M_{(LFGR)} \times GWP_{CH_4} \quad \text{...} \; 15$$

where, GWP_{CH4} is the global warming potential of methane gas relative to carbon dioxide and given as 25 kg CO_2/kg CH_4 (Ryu, 2010). As, in this scenario, there is no electricity production from methane emissions. So, all this methane is to be considered in estimation of GWP for business as usual.

3.7.1.2. Second scenario (LFG)

Disposal of all municipal solid waste in landfill (except inert and recyclable materials) and biogas recovery system was installed to generate electricity from collected methane.

Methane collection efficiency is assumed 60% in this study, which is suggested by other studies (Ogunjuyigbe et al., 2017). Furthermore, 25% methane is assumed to be leaked out into atmosphere after capturing which contributes to global warming (Ayodele et al., 2017). The following equation can be used to determine the methane emissions (leakages) in tons for second Scenario in this study.

$$M_{(LFGR)}(\text{ton/year}) = Q_{CH4(LFG)}(t) \times \lambda \times 0.00667$$

Here, λ is the collection efficiency of biogas from landfill ranges from 50 to 90% (EPA, 2011). In current study 75% collection efficiency is used according to literature (Ayodele et al., 2017). For second scenario the methane equivalent of carbon-dioxide ($M_{CO_{2eq}(LF)}$) is obtained from following equation.

$$M_{CO_{2eq}(LF)(\text{tons/year})} = M_{(LFGR)} \times GWP_{CH_4} \quad \text{.................................} \; 16$$

To estimate the global warming potential of LFG technology with energy recovery system, for the generation of one GWh electricity, following equation can be used:

$$LFG\left(\frac{GWP}{GWh}\right)\text{tons/year} = \frac{M_{CO_{2eq}(LF)(\text{tons/year})}}{EP(LFGR)}$$

3.7.1.3. Third scenario (AD)

Estimation of GWP, using methane produced through the AD technology to generate electricity.

The amount of carbon dioxide in biogas which is removed during purification of biogas, and the amount of CO_2 that is released due to combustion of methane in internal combustion engine (ICE) plant is biogenic in origin, therefore it is assumed as carbon neutral (Mohareb et al., 2011).

The other GHGs such as methane and nitrous oxides emissions from ICE during electricity production are very small and these emissions are lesser as compared to other technologies in waste-to-energy sector. So, the estimation of these gasses is not required (IPCC, 2006). However, the certain amount of methane that leaked out from reactor organic fraction of MSW, had higher contribution in greenhouse effect, in AD facilities. According to IPCC, 5% of produced methane is leaked out from digester (IPCC, 2006). Therefore, the methane leakages from Anaerobic digester plant (in ton) are obtained as follow.

$$\mathrm{M}_{\mathrm{CH_4(AD)(tons/year)}} = 0.05 \times \mathrm{CH}_{4(\mathrm{AD})} \times \boldsymbol{\rho}_{\mathrm{methane}} /1000$$

Where, $\boldsymbol{\rho}_{methane}$ is the density of CH_4 which is 0.717 kg/m^3 (MIT, 2007), CH_4 is the actual volume of methane produced using AD technology, $\mathrm{M}_{\mathrm{CH_4(AD)}}$ is the quantity of methane leaked out into atmosphere. So, the methane equivalent of carbon dioxide (CO_2-eq) can be estimated as:

$$\mathrm{M}_{\mathrm{CO_{2eq}(AD)tons/year}} = \mathrm{M}_{\mathrm{CH_4(AD)}} \times \mathrm{GWP}_{\mathrm{CH_4}} \quad \text{……………………….. 15}$$

where, GWP_{CH_4} is the global warming potential (GWP) of CH_4, which is 25 $kgCO_2/kgCH_4$ (Ryu., 2010). To calculate the global warming potential of AD technology with energy recovery system, for the generation of one GWh electricity, following equation can be used:

$$\mathrm{AD}\left(\frac{\mathrm{GWP}}{\mathrm{GWh}}\right)\mathrm{tons/year} = \frac{\mathrm{M}_{\mathrm{CO_{2eq}(AD)(tons/year)}}}{\mathrm{EP(AD)}}$$

3.7.2. Displacement of diesel with equivalent of biogas (methane)

In this study, efforts are made to calculate the amount of diesel that would be displaced when the estimated methane from AD and LFG technology is used in internal combustion engine, to produce equivalent amount of power instead of diesel. This part will help in estimation addition benefits of current study other than the MSW management and energy generation. The amount of displaced diesel (D_d) in liters, i.e., when the estimated methane in 20 years period from both technologies, is used to produce equivalent amount of power (electricity), as produce by using diesel as fuel source, can be estimated as:

$$D_d(i) = FE_d \times E_P(i)$$

Here, FE_d is the fuel efficiency of diesel generator. Its value is taken as 0.33 L/kWh (Cader et al., 2016). i represents AD or LFG technology. E_P represents the amount of electricity in kWh generation estimated in this study for both technologies.

3.7.3. Avoided CO_2 emissions due to displacement of diesel by methane

The methane can be used in internal combustion engine instead of fossil fuels to generate electricity. In this study, methane is compared with diesel items of CO_2 emission during electricity production from both sources through internal combustion engine. Among various fossil fuel, diesel is selected in current study for comparison because diesel’s contribution in energy mix of Pakistan is huge. The avoid CO_2 emissions due to usage of methane in internal combustion engine instead of diesel, can be calculated as.

$$A_C = D_d(i) \times S_{EF}$$

Where, S_{EF} is the specific emission factor of carbon dioxide from diesel fuel and its value is taken as 2.7 (kg CO_2 / liter) (Ayodele et al., 2018). i is the type of technology (i.e., AD or LFG technology).

3.8. Estimations of externalities (cost of 1-ton GHGs emission into atmosphere)

Externalities are additional outcomes of any project which could be beneficial or harmful. The social cost of carbon dioxide (S_C (CO_2)) includes all the impacts of climate change caused by the emission of CO_2, on all market and non-market sectors, such as energy production, water availability, agriculture, human health, biodiversity, coastal communities etc. (Marten and Newbold, 2012). The standard unit used in estimation of social cost of CO_2 is dollar per metric ton of CO_2. So, by reducing its emissions (in tons), the social cost of cardon can be avoided during any project. The social cost of carbon is an estimation of net present value of monetized social damages caused by emission of metric ton of CO_2 in atmosphere. US government calculated social cost of one ton of carbon dioxide (S_C (CO_2)) emission in atmosphere, which is 46 dollars for one metric ton of CO_2 release in atmosphere, in accordance with 2016-dollar rates (IWG 2016). The CO_2 is not only greenhouse gas (GHG), other gasses responsible for greenhouse effect, includes methane, nitrous oxides, water vapors, hydrofluorocarbons. All these gasses have different global warming potential (GWP). For better comparison, it is easier to convert cost for reducing non-CO_2 gasses into carbon dioxide-equivalent units. The ratio between the marginal cost of carbon dioxide and those of methane and nitrous oxides are roughly equal to the GWP of these gasses (Enkvist et al., 2007). The 100-year GWPs of methane and nitrous oxide, reported by IPCC are 25 and 298, respectively (Gillingham and Stock, 2018).

Methane produce during lifetime of project is collected and used for production of electricity, if this amount of methane is not collected from landfill and releases into atmosphere than it can cause huge environmental impact. So, the amount of methane equivalent to CO_2 in tons per year ($M_{(LFG)}$ tons/year), without energy recovery system from LFG technology can be calculated using Equation 15.

The avoided social cost of methane S_C (CH_4) equivalent to CO_2, that could be release into atmosphere can be calculated as:

$$S_C\,(CH_4)\,(t) = M_{(LFG)}\,(\text{tons/year}) \times S_C\,(CO_2)\text{ Per ton} \times 25$$

By incorporation this social cost in our study, we can estimate the financial parameter in this study with the addition of externalities.

3.9. Sensitivity analysis

Sensitivity analysis shows the dependency of a given system characteristic on some defined input variables (Ogunjuyigbe and Ayodele, 2016).

Table 3.9 Input values of variable for sensitivity analysis

Inputs	Variations in inputs					
USD to PKR exchange rate (PKR)	160	170	180	190	200	205
Feed in tariff (PKR)	10.32	11.32	12.32	13.32	114.32	15.32
Marginal sales tax rate (%)	31%	29%	27%	25%	23%	21%

It helps us to understand the impacts of variations in inputs that have magnificent role in determination of economic viability of projects. In this study the sensitivity analysis of AD technology is conducted by varying the values of three inputs. These inputs are USD vs PKR currency exchange rate, feed in tariff, and marginal sales tax rate which are shown in the Table 3.9. Sensitivity analysis is applied on NPV and IRR by varying the input factors given in the Table 3.9.

CHAPTER 4

4. RESULTS AND DISCUSSION

In this chapter, results of the study are presented in graphical and tabular form, and the results of each part of the study are thoroughly discussed and compared with existing literature. Furthermore, the reason for deviation of some results from previous literature is discussed with references. Results related to MSW generation projection, economic indicators, sensitivity analysis, and environmental impacts (GWP), are presented to meet each objective of the study.

4.1. MSW generation projection

Figure 4.1 illustrate the amount of MSW generation in Lahore city throughout the project's life period of 20-years. In the first year of project the MSW generation in Lahore city is 3289336.12 tons in 2021, which increase to 13300278.42 tons till the end of project in 2040.

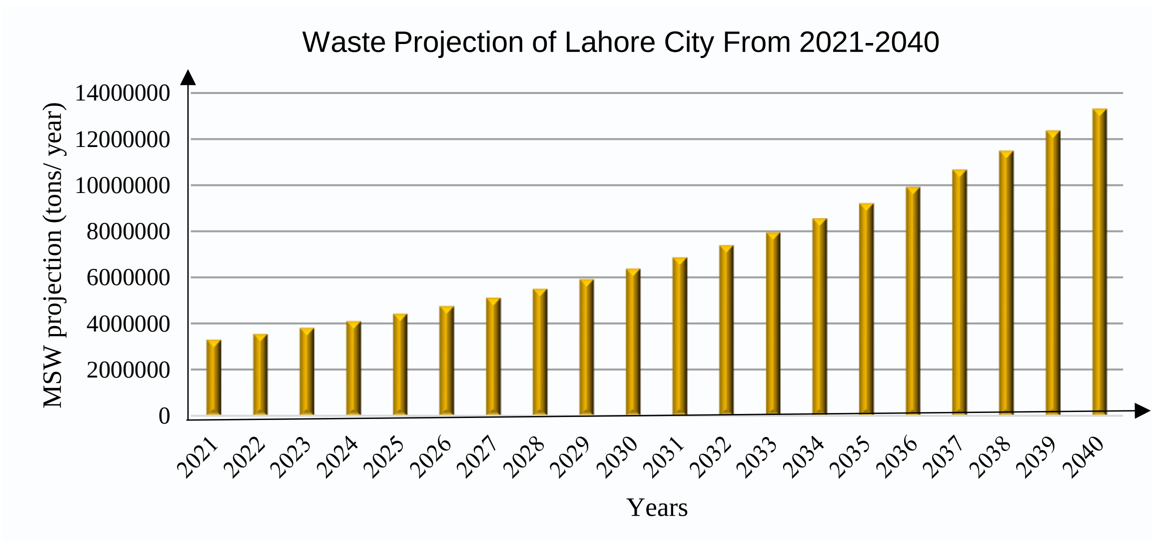

Figure 4.1 MSW generation projection for Lahore city from 2021 to 2040

This waste generation depends upon population and per individual waste generation rate. In this study, the increase in waste generation in 20-year life period of project is 304.35%. In another same study conducted by Huang and Fooladi in Tehran, the percent increase in MSW generation is 340% (Huang and Fooladi, 2021). This slight difference is due to different waste generation rate of per person and population growth rate, in both cities. As, the population growth rate in Lahore is 3.73% (PBS, 2017), this rate is higher than the population growth rate in Tehran which is 1.95% (Huang and Fooladi, 2021) so this factor contributes to higher percent of MSW generation over the life period of project.

4.2. Methane generation potential from AD and LFG technology

Table 4.1 shows that during the 20 year of projects the total methane production potential is 43093948063 and 1666922047 m^3 from AD and LFG technologies respectively. While the total waste generation potential for Lahore city during lifetime of project is 144501024.4 tons. So, the stoichiometric calculations show that in current study, one ton of MSW have potential to produce 298.2 m^3 of methane, in-case of AD technology, while 11.52 m^3 methane will produce from one ton of MSW using LFG technology.

According to Ayodele and his co-works, one ton of MSW have potential to produce 219.7 m^3 of methane through AD technology (Ayodele et al, 2018). This value is slightly lower that the methane production value in this study because of difference in collection efficiency of MSW in both Lahore and Ibadan city. In their study, Ayodele and his co-workers used 76% MSW collection efficiency while in case of Lahore its value is 95% (EPD, 2016). This means they use less percent of total generated MSW in AD facility while in this study higher percent of waste is used from the total generated MSW in Lahore city, which caused higher methane production potential per ton of MSW. Furthermore, by comparing carbon and hydrogen concentration in MSW of both studies using ultimate analysis, reveals that in Ayodele’s work, hydrogen, and carbon percentage in chemical formula of MSW is 52% and 5.6% respectively (Ayodele et al, 2018), which is lower as compared to current study where chemical formula of MSW had higher percentage of carbon and hydrogen which is 62% and 7%, respectively. Due to higher carbon and hydrogen concentration in MSW of current study, the methane production from per ton of MSW is higher as compared to the study conducted by Ayodele in Ibadan, Nigeria.

Methane production per ton MSW in this study is lower than the study conducted by Ayodele and his fellows by using LFG technology, which is 148.3 m^3 per ton of MSW (Ayodele et al, 2018). This is because of difference in values of L_o (potential methane generation capacity) and K (Methane generation constant), in both studies, which are used in landGem model to evaluate methane production potential of MSW by LFG technology. L_o mainly depends upon organic fraction of MSW and average temperature of study area. As, in this study the biodegradable organic fraction is 56.2% (Azam et al, 2020), which is less than the organic fraction of MSW used in Ayodele's study which is 76.0% (Ogwueleka., 2009). The second important factor in calculation of Lo is temperature. The average annual temperature in Lahore city is 24.0 °C (Nasar-u-Minallah & Ghaffar, 2020), which is lesser than average annual temperature of Ibadan city which is 34.0 °C (Fabeku et al, 2018). In the calculation of 'K' the main factor is annual rainfall. In Ayodele's study its value is 1467 mm (Egbinola and Amobichukwu, 2013) and in Lahore average annual rainfall is approximately 628.6 mm (Siddiqui-R and Siddiqui-S, 2019). So lower organic biodegradable fraction of MSW, lower temperature and lower annual rainfall in Lahore contributes less methane production from LFG facility in this study.

Table 4.14 Methane production from the projected waste of Lahore by AD and LFG technology

Year		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Methane produced $\times 10^6$ (m^3/ year)	AD	981	1055	1136	1223	1316	1416	1525	1641	1766	1901
	LFG	05	11	17	23	30	37	44	52	60	69
Year		**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Methane produced $\times 10^6$ (m^3/ year)	AD	2046	2202	2370	2551	2746	2955	3181	3424	3685	3966
	LFG	78	88	98	109	121	134	148	162	178	194

4.3. Electricity generation potential of AD and LFG technologies

In literature, composition of MSW and its collection efficiency in existing studies are different. So, to compare results with literature, the average MSW generation in each year is calculated and compared it with average electricity generation potential in each year. Furthermore, electricity generation in GWh from one ton of MSW is also calculated in different study for better comparison.

In this study, the average waste generation per year is 7225051.2 tons/year, which produce 6623.8 (GWh/year) electricity in case of AD technology while the LFG technology has average electricity generation potential of 172.9 GWh/year. This shows that 0.0009 and 0.00002 GWh electricity is produced through AD and LFG technology respectively, from one ton /year of generated MSW.

In case of AD technology, electricity generation potential from each ton of MSW is higher as compared to study conducted by Ayodele and his co-workers, in Ibadan city Nigeria, which are 0.0007 GWh from one ton of MSW (Ayodele et al, 2018). This is because of lower collection efficiency of MSW in Ibadan city. Which is 76%. While in case of Lahore, the waste collection efficiency is 95% (EPD, 2016). so, more waste would be feed to AD digester. According to another study conducted by Cudjoe and his fellows in Beijing, China, the electricity generation potential from one ton of MSW is lower than the current study which is 0.0001 GWh/ton, due to lower organic content of waste (i.e., 52.6 %) (Cudjoe et al., 2020).

In case of LFG technology, per ton waste potential to generate electricity in this study is lower as compared to study conducted by Ayodele and his fellows which is 0.0004 GWh electricity generation from one ton of MSW (Ayodele et al., 2018). In current study the electricity generation from LFG technology is lesser because the biogas production is less and because of climatic condition and composition of municipal solid waste in the study area.

Table 4.15 Electrical energy generation over the lifetime of AD and LFG technologies

Year		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Energy generated (GWh)	AD	3015	3246	3493	3760	4046	4355	4688	5045	5430	5845
	LFG	12	23	36	49	62	77	92	108	125	143
Year		**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
Energy generated (GWh)	AD	6291	6771	7287	7843	8442	9086	9779	10526	11329	12193
	LFG	162	183	204	228	252	279	307	337	369	404

4.4. Economic assessment of the technologies

In current study, important economic parameters are used to estimate the economic viability of AD and LFG technology for Lahore city, which includes TLCC, NPV, LCOE, PBP, and IRR. The LCOE was evaluated yearly over the lifetime of the projects while the other metrics were determined for the whole lifetime of the project. The Total life cycle cost (TLCC) of both AD and LFG technology is shown in table 4.4 and 4.5.

4.4.1. Levelized cost of energy (LCOE)

The LCOE decreases from 0.0886 USD/kWh in 2021 to 0.0154 USD/ kWh in 2040 for AD technology while on the other hand, the LCOE decreases from 2.2689 USD/kWh in 2021 to 0.0700 USD/kWh in 2040, when LFG technology is used, depicted in Table 4.3. This is expected because the amount of electricity production depends on the amount of biogas yield which is in turn dependent on the amount of feedstock available for the energy conversion technology. The amount of feedstock increases yearly as being depicted in Figure 4.1.

Table 4.16 Yearly LCOE over the lifetime of the project implementation using the two technologies

Year		**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
LCOE (USD/ kWh)	**AD**	0.088	0.079	0.071	0.064	0.058	0.053	0.048	0.043	0.040	0.036
	LFG	2.268	1.158	0.768	0.568	0.446	0.364	0.305	0.260	0.225	0.197
Year		**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
LCOE (USD/ kWh)	**AD**	0.033	0.030	0.027	0.025	0.023	0.021	0.0198	0.018	0.016	0.015
	LFG	0.174	0.154	0.138	0.124	0.112	0.101	0.092	0.083	0.076	0.070

In case of AD technology, nearly same results are found in Ayodele's study with similar work, in which LOCE for AD technology ranges from 0.0681USD/kWh in 2017 to 0.0336 USD/kWh in 2036. These values have similarities with another referred study (Ogunjuyigbe et al., 2017). The LOCE of LFG in Ayodele's study ranges from 0.2411USD/kWh in 2017 to 0.0350 USD/kWh in 2036 (Ayodele et al., 2018), these values are lower than the values in this study because of lower methane production from landfill due to lower values of Lo (potential methane generation capacity) and K (Methane generation constant) in this study. In another study with the same work conducted by Cudjoe and his co-workers, in Beijing city, have close agreement with the results of the study, which are 0.0739 USD/kW and 0.1413 USD/kW average LOCE for AD and LFG technologies respectively (Cudjoe et al., 2020).

4.4.2. Net present value (NPV)

Table 4.4 and 4.5 shows that AD technology is economically viable with positive NPV of 616.64 million USD and LFG technology is not viable with negative NPV of -650.8 million USD. In this project the higher NPV of AD technology is due to higher volume of biogas generation from AD digester which ultimately contribute to electricity generation. LFG technology has negative NPV according to given climatic conditions in this study, which are used in LANDGEM model which are discussed above. This trend is in accordance with (Cudjoe et al., 2020) and area (Ayodele et al., 2018) which discovered that AD technology has nearly double positive net present value than the NPV of LFG technology, but in this study the NPV of LFG technology is negative because of lesser potential of methane generation from landfill which have significant role in production of electricity.

4.4.3. Internal rate of return (IRR)

In this study the IRR is 1.86% for AD technology and -8.88 % for LFG technology, shown in Table 4.4 and 4.5. In another referred studies the IRR of AD technology is lower than the LFG technology (Ogunjuyigbe et al., 2017); (Ayodele et al., 2018).

4.4.4. Payback period (PBP)

Table 4.4 and 4.5 shows that payback period of AD technology is 17 years and LFG technology can't recover its investment, so payback period is not possible in this case. In another similar study the payback period is 5.2 years and 6.7 years for AD and LFG technologies respectively (Ayodele et al., 2018). The higher pay back period in this study is due to lower bio-degradable fraction of MSW that are used as feedstock in AD technology. In case of LFG technology, the biogas generation from landfill is less due to which PBP is beyond the project life period of 20 years.

Table 4.17 Results of economic parameters over the lifetime of project implementation for AD technology

Economic metrics	Units	Without externalities	With externalities
Total Life cycle cost (TLCC)	Million USD	4343.5	4343.5
Net present value (NPV)	Million USD	616.64	3139.8
Payback period (PBP)	Years	17.89	17.89
Internal Rate of Return (IRR)	%	1.86	6.0

Table 4.18 Results of economic parameters over the lifetime of project implementation for LFG technology

Economic metrics	Units	Without externalities	With externalities
Total Life cycle cost (TLCC)	Million USD	562.7	562.7
Net present value (NPV)	Million USD	-VE (-650.8)	366.6
Payback period (PBP)	Years	-VE	-VE
Internal Rate of Return (IRR)	%	-VE (-8.8)	4.4

4.5. Economic indicators with addition of externalities

In this study the social cost of methane released from landfill is calculated according to Intragency Working Group on social cost of greenhouse gases (IWG 2016). This social cost is used in this study as externalities of the projects. This is because in present time the total MSW of study area is managed by open dumping in landfills which release methane into the atmosphere. When AD technology or LGF gas recovery technology would be used then it can prevent this methane emissions. By adding the cost of externalities with cash flows, the economic matrices such as NPV, IRR and PBP is calculated in this study.

Table 4.4 and 4.5 shows that with the addition of externalities the NPV of AD and LFG technologies are 3139.8 million USD and 366.6 million USD respectively. This increase in NPV is due to addition of positive cash flows in the calculation of NPV. Furthermore, with addition of externalities cost, the NPV of LFG technology also get positive, so with the cost of externalities both AD and LFG technologies are economically viable for Lahore city.

Table 4.4 and 4.5 also depicts that the IRR of both AD and LFG technologies are reduced to 6% and 4.4% respectively. This parameter also suggests the higher economic viability of both technology with the consideration of environmental benefits in the form of avoidance of social cost of methane.

4.6. Sensitively analysis of AD technology

In this section, results of sensitivity analysis are presented for AD technology. Sensitivity analysis is conducted upon two vital economic parameters which are NPV and IRR by varying currency exchange rate, feed in tariff, and marginal sales tax rate.

4.6.1. Currency exchange rate

Figure 4.2 and 4.3 depict that the dollar exchange rate in Pakistan had huge impact on economic viability of AD project. In this study, the exchange rate of USD vs PKR is taken as 160 PKR equals to 1 USD, but this rate is highly unstable in the country, so the economic viability of AD project is analyses under different Dollar exchange rates.

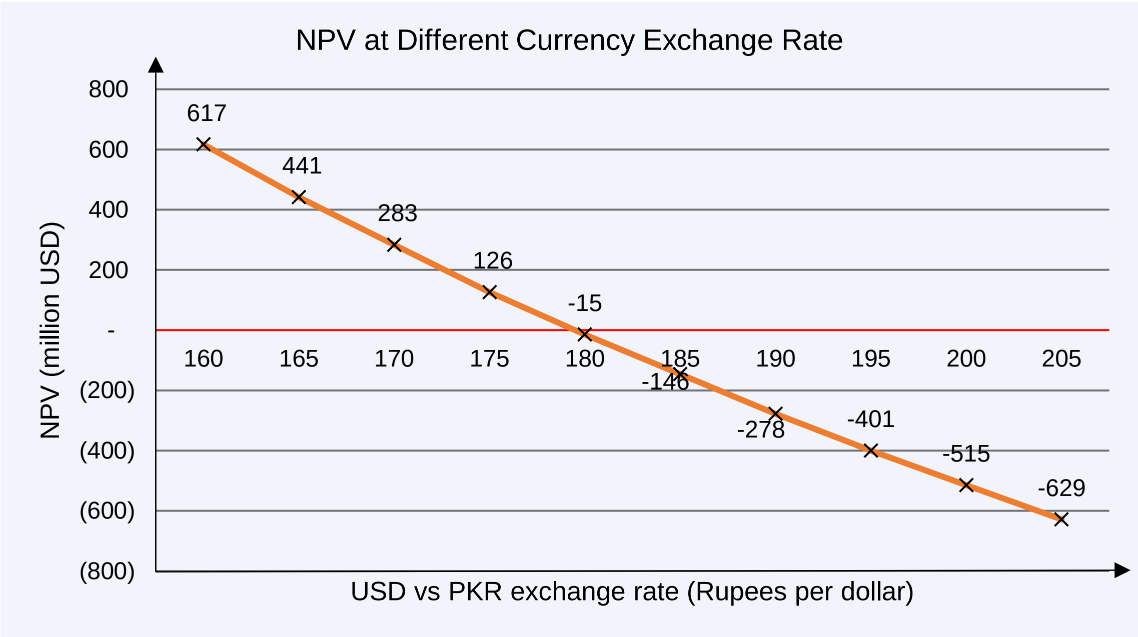

Figure 4.2 NPV of AD technology at different currency exchange rate

At lowest dollar exchange rate of 160 PKR per USD, the NPV of AD project is 616.64 million USD and IRR to 1.86%, while if the dollar exchange rate increases to 205 PKR per USD, then both NPV and IRR would be negative which is -628.51 million USD and -0.96% respectively, when all other factors are kept constant in the study.

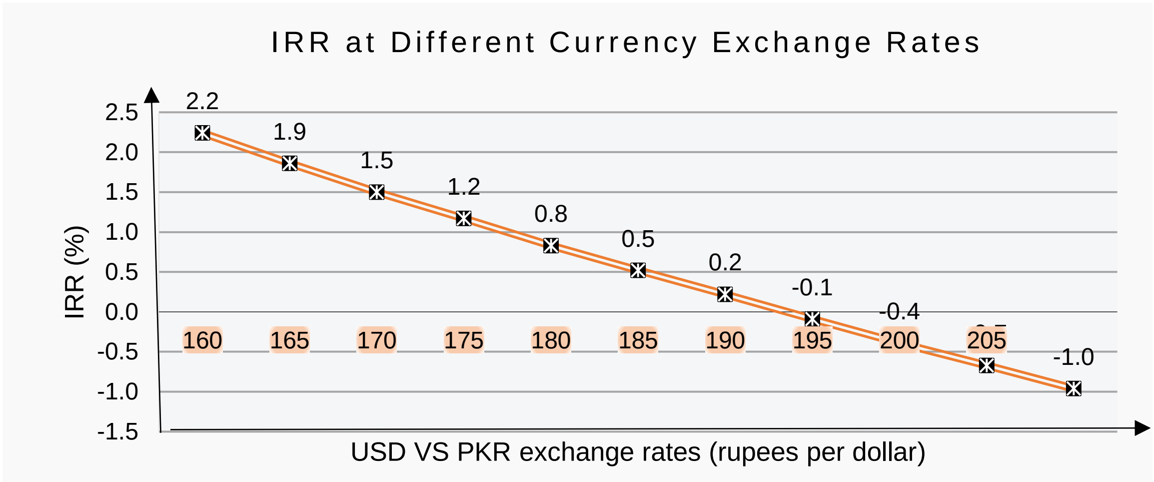

Figure 4.3 IRR of AD technology at different currency exchange rate

4.6.2. Feed in tariff

Feed in tariff directly effects the revenue generation from the project, so variation in feed in tariff had huge impact on economic viability of the project. In Pakistan, the current value of feed in tariff for electricity generation from renewable energy sources are 10.3 PKR/ kWh electricity (NEPRA, 2018), which is equal to 0.0645 USD at the dollar rates of 2021.

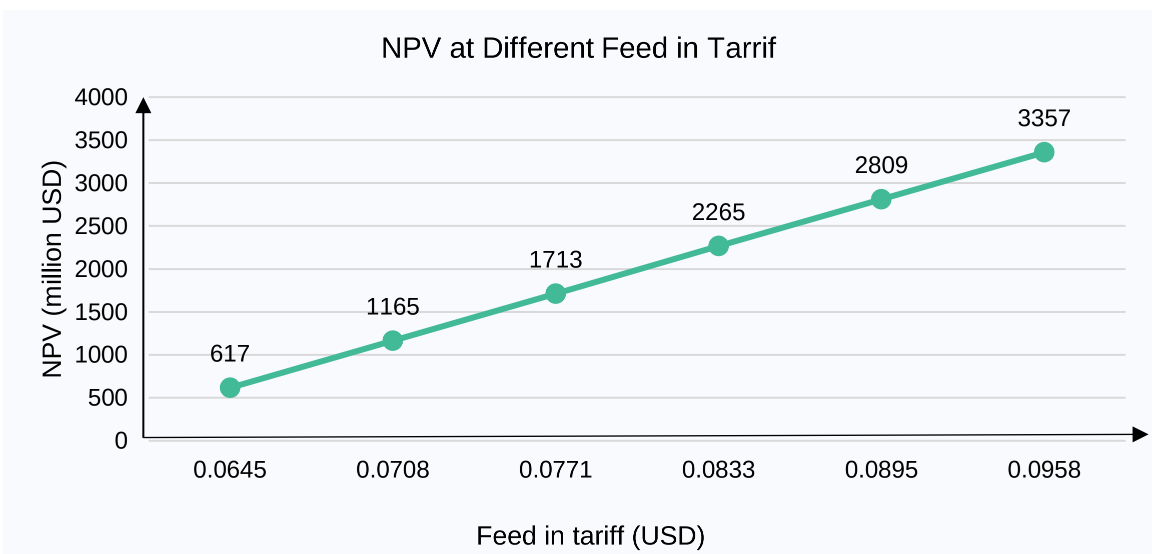

Figure 4.4 NPV of AD technology at different feed on tariff

Results of sensitivity analysis at different feed on tariff rates for NPV and IRR of AD technology is depicted in Figure 4.4 and 4.5. This shows that if the feed in tariff is increase to highest value which is taken as 15.32 PKR/kWh (0.0958 USD/kWh) then the NPV and IRR would be highest which are 3357.03 million USD and 6.47%, respectively. So, the governments can subsidize the electricity which is generated through renewable energy generation technologies by increasing feed in tariff.

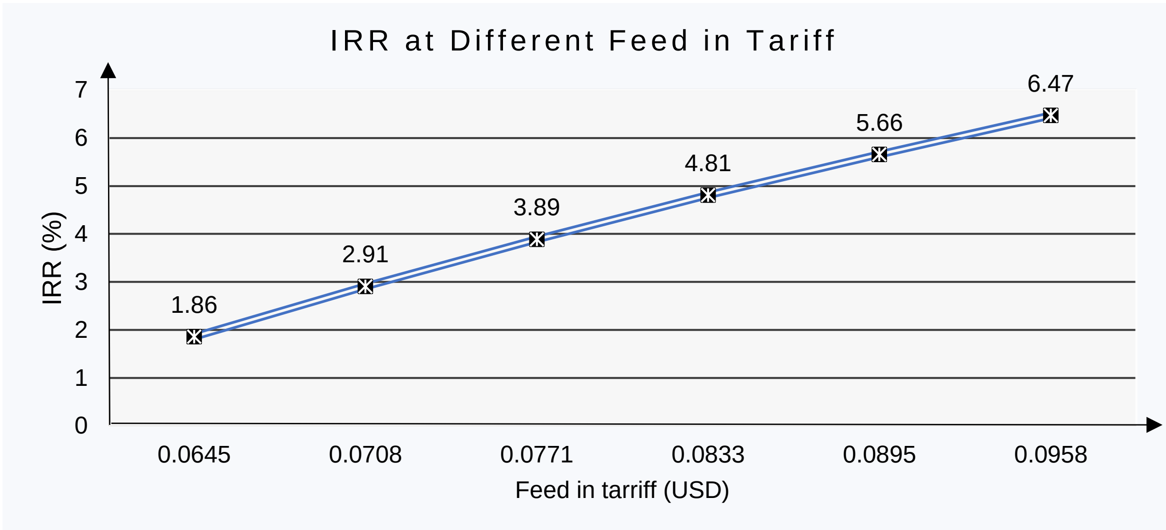

Figure 4.5 IRR of AD technology at different feed on tariff

4.6.3. Sales tax rate

Sales tax influence the profit of AD digestion project and have important role in determination of economic viability of the project, currently, in Pakistan the sales on industrial products and services are 29% (Nazir et al., 2020).

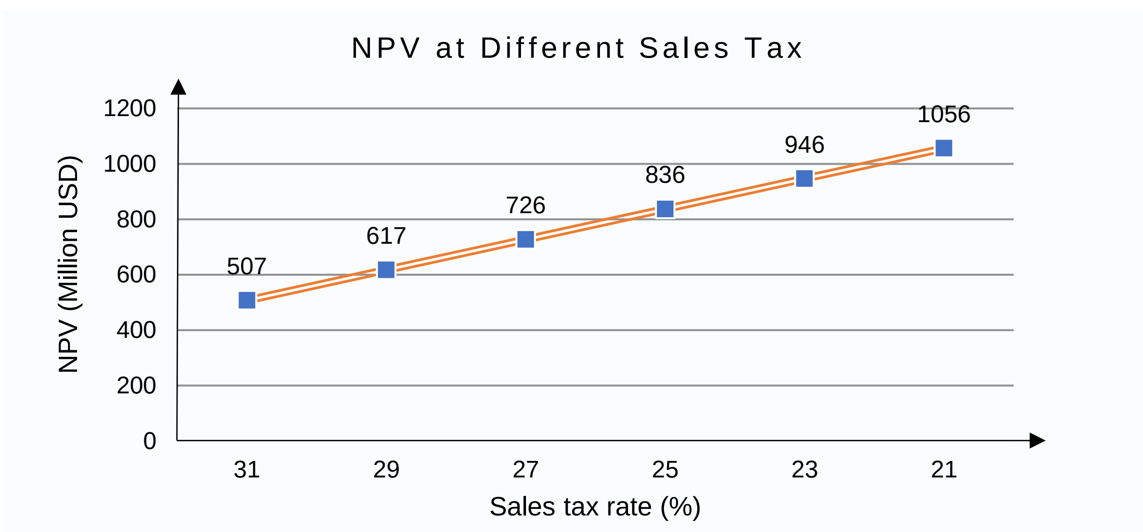

Figure 4.6 NPV of AD technology at different sales tax rate

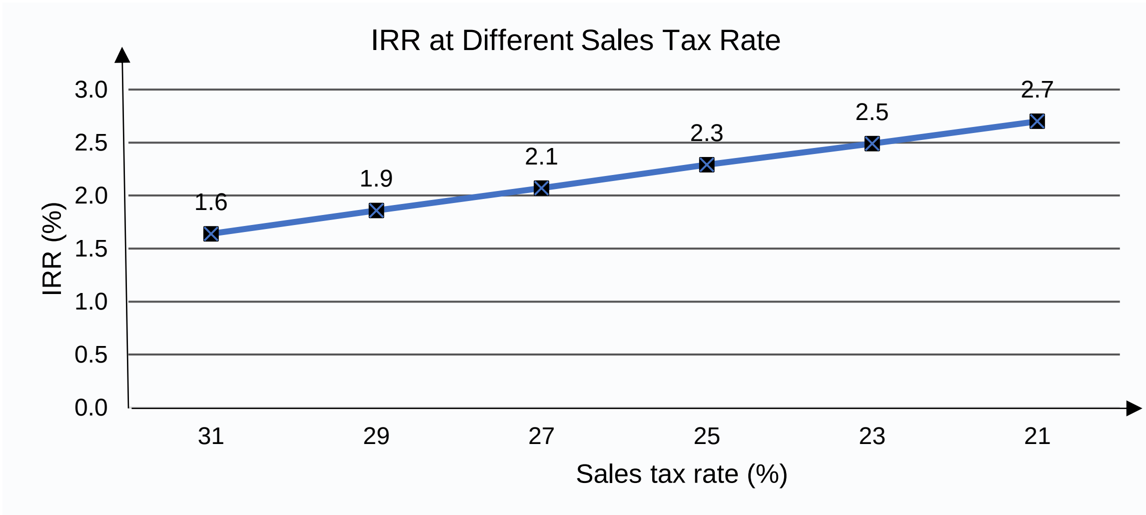

Figure 4.7 IRR of AD technology at different sales tax rate

In this study, different sales tax rates are used in sensitivity analysis to analyze the magnitude of possible change in economic parameters such as NPV and IRR for AD technology. Figure 4.6 and 4.7 shows that at highest sales tax rate (i.e., 31%) the NPV and IRR of AD technology is reduced to 506.85 million USD and 1.68% respectively, while at lower sales tax rate (i.e., 21%) used in this study, the NPV and IRR increase to 1055.8 million USD and 2.70% respectively.

4.7. Greenhouse gases (GHGs) emission assessment of biogas recovery technologies using life cycle assessment

Figure 4.8 depicts the global warming potential (GWP) of AD and LFG technologies under different scenarios. It was found that scenario 3 (AD), in which biogas is produced through anaerobic digestion process to generate electricity, had highest GWP of 38622.9 ktons CO_2 eq in 20-year period. Scenario 2 (LFG) has lowest GWP of 6254.1 ktons CO_2 eq in 20-year period, where all the MSW is disposed in landfill with energy recovery system. In scenario 1(business as usual), where all the MSW is disposed in landfill without energy recovery, had GWP of 25016.3 ktons CO_2 eq in 20-year period shown in figure 4.8.

Scenario 3 had highest GWP because of higher amount of methane is produced using AD technology during life period of project, as compared to scenario 2 and 3, where LFG technology is used, and total methane production is lesser in 20-year period. While the GWP of scenario 2 is noticed lower than scenario 1 in this study.

In another similar work, conducted in Beijing and Tehran with same scenarios, the GWP values of scenario 3 is noted lesser than scenario 1 and 2, which differ from our study (Huang and Fooladi, 2021). This is because in their case the total methane production from AD is lesser than our study which is discussed earlier. In Huang and Fooladi work scenario 2 had lower GWP than scenario 1 which is similar to work in current study (Huang and Fooladi, 2021).

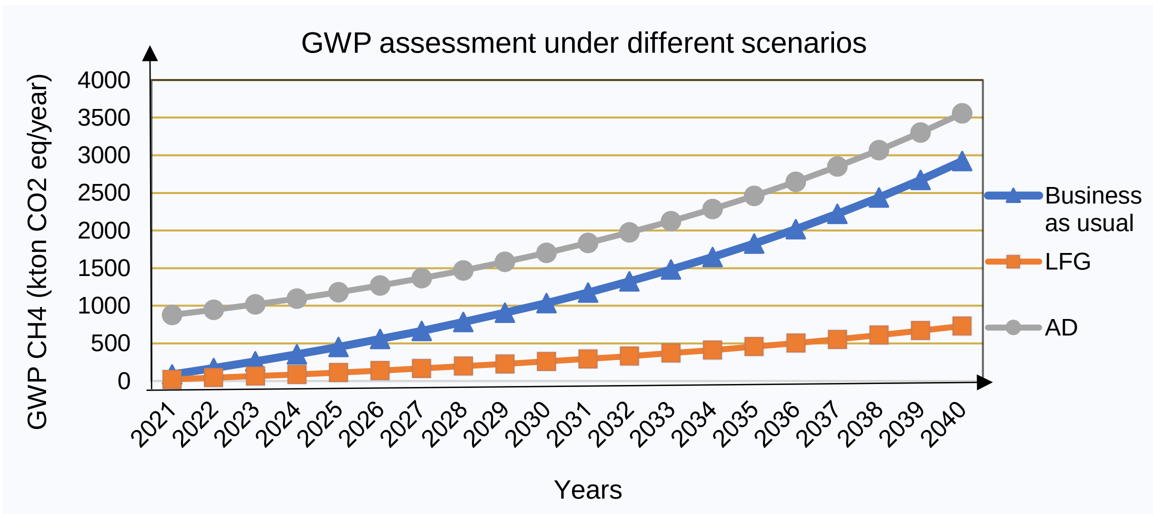

Figure 4.8 Environmental assessment (GWP) of AD and LFG under different scenarios

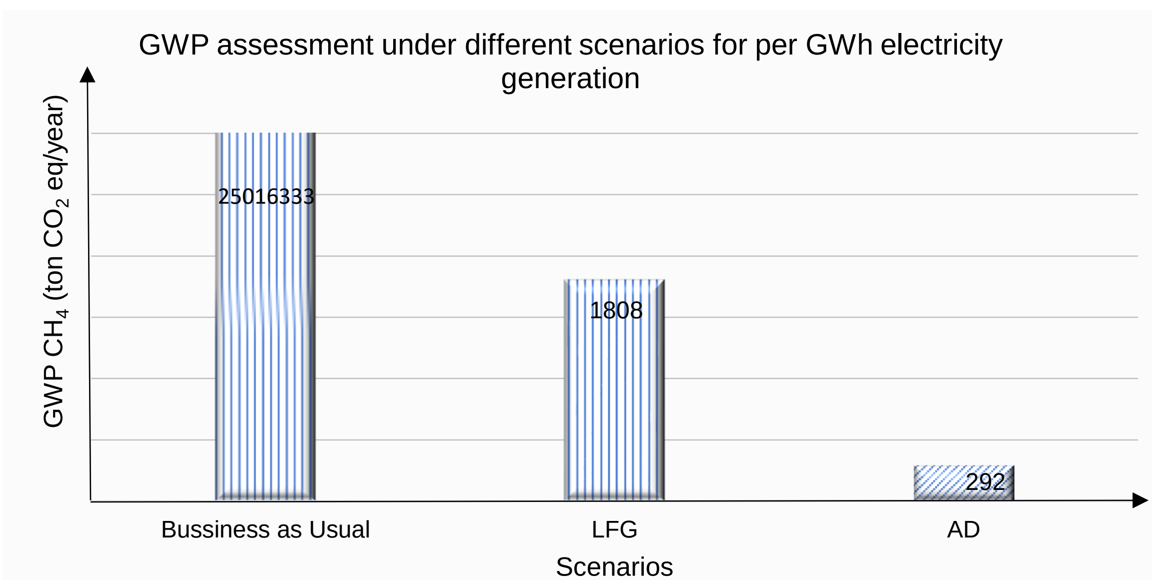

Figure 4.9 GWP of AD and LFG technologies under three scenarios for generation of per GWh energy

For better comparison, the GWP of both technologies in terms of CO_2-eq methane in tons is calculated in three scenarios for the generation of one GWh electricity. Results show that business as usual have highest GWP which is 25016333 tons of $CO_{2\text{-}eq}$ methane, because in this scenario, there is no electricity production. So, total methane emissions are taken in GWP assessment. Furthermore, GWP of LFG technology is higher than that of AD technology, which is 1808 and 292 tons CO_2-eq, respectively, for the generation of one GWh electricity. These results are similar with the study conducted be Huang and Fooladi (Huang and Fooladi, 2021).

4.7.1. Avoided diesel and CO_2 from AD and LFG technology

Table 4.6 depicts that, in current study, due to usage of estimated methane in internal combustion engine, 43717.7 megaliters of diesel can be replaced in case of AD technology which is higher than that of LFG technology i.e., 1141.4 megaliters. Furthermore, AD technology can contribute in 118037.8 ktons avoidance of CO_2 emissions in atmosphere which is higher than the estimated avoidance of CO_2 emissions in case of LFG technology. Despite of difference in quantity, both technologies can contribute is reduction of diesel usage for energy purposes and ultimately reduce the emissions of CO_2 in atmosphere. These benefits make MSW as sustainable source of energy with less environmental degradation.

Table 4.6. Avoided diesel and CO_2 due to AD and LFG technology in 20-years project life

Sr no.	Technology	Avoided diesel in ICE (Megaliter)	Avoided CO_2 emission (ktons)
1	AD	43717.7	118037.8
2	LFG	1141.4	3081.78

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In present study, energy generation potential from MSW of Lahore, through AD and LFG technology are investigated. For this purpose, waste generation potential of the city over 20-years period is determined. Methane generation potential of OFMSW is estimated for both technologies. Beside this, the electricity generation potential from both technologies is also investigated. Economic viability of AD and LFG technology is investigated using economic indicators such as TLCC, LCOE, NPV, IRR and PBP. These parameters are also analyzed with and without addition cost of externalities. Sensitivity analysis for economic viability of both projects is carried out by varying USD vs PKR exchange rate, marginal tax rate and feed on tariff. Environmental assessment was carried out by calculating GWP of both technologies under different scenarios. From results, it is concluded that from 2021 to 2040, the total MSW generation potential of Lahore city is 14450 ktons. The methane generation potential is found to be (43093 and 1954) $\times 10^6$ m^3 for AD and LFG technology, respectively. Furthermore, the electricity generation potential of AD and LFG technologies are 132477 and 4056 GWh respectively. Furthermore, the AD technology is found to be economically viable with positive NPV of 616.4 million USD, even without adding the cost of externalities, while the negative NPV which is -650 million USD is estimated for LFG technology which shows that it is not economically viable in the region but with addition of externalities cost the LFG project become economically viable and NPV turns positive which is 366 million USD. IRR is positive for AD technology which is 1.86% while it is negative for LFG technology (i.e., -8.8%). These both are important economic indicators that suggest the AD as more economically viable as compared to LFG technology. Sensitivity analysis of LFG technology not conducted because of negative NPV. So, it is considered economically unviable. Results of sensitivity analysis shows that at lower currency (USD vs PKR) exchange rates, the NPV and IRR of AD technology increases and vice versa. At lowest currency exchange rate which is 160 PKR /USD, analyzed in this study, the NPV and IRR of AD technology increases to 616 million USD and 1.8% respectively. While at highest feed on tariff (i.e., 0.0958 USD) in the study, the

NPV and IRR of AD technology increases which reaches to 3357.03 million USD and 6.47% respectively. At lowest value of marginal tax rate used in this study which is 21%, the NPV and IRR goes highest which is 1055.8 million USD and 2.70% in case of AD technology. Results of environmental assessment show the GWP of LFG technology is higher than that of AD technology, which is 1808- and 292-tons CO_2-eq, respectively, for the generation of one GWh electricity. Sensitivity analysis also suggest that AD technology is more economically viable than LFG technology but by varying some important factors that are used in sensitivity analysis, the LFG technology also shows positive NPV, which means that LFG technology can also be used as economically viable technology if the mentioned input factors are controlled and adjusted. This study is first-hand information that can be used by policy makers and governments for selection of waste to energy technology for Lahore Pakistan.

5.2 Recommendations

AD technology is recommended for Lahore in this study for the generation of electricity from organic fraction of MSW. Biodegradable and non-biodegradable MSW should be segregated on source site to avoid wastage for better management of MSW. Work should be done on technical aspects of AD and LFG technology to improve their efficiency. Efficiency of internal combustion engine (ICE) directly impacts on energy generation from methane generates form AD and LFG technology, so efforts are required in increasing efficiency of ICE. For better financial estimates, pilot scale setups of AD technologies should be installed. Economic assessment in this study is based on cost of AD and LFG technology in international market which adversely effects economic analysis because of poor currency in Pakistan, so work should be done on local production of these technology, to reduce their cost.

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ANNEXES

1) Calculation of total MSW generation for 2021

$P_{OP}(t) = P_{OP_{base}} \times (1 + r_{pop})^t$

$P_{OP}(t) = 12881537.19 \times (1 + 0.0373)^1 = 13362018.5$

$W_{GR}(t) = W_{GR_{base}} \times (1 + q)^t$

$W_{GR}(t) = 0.65 \times (1 + 0.0376)^1 = 0.67444$

$MW_G(t) = \frac{(P_{OP}(t) \times W_{GR}(t) \times 365)}{1000}$ tons/yr

$MW_G(t) = \frac{(13362018.5 \times 0.67444 \times 365)}{1000} = 3289336.12$ tons/yr

2) Calculation for methane production from AD technology for 2021

$$C_wH_aO_bN_c + \left(w - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right) H_2O ==> \left(\frac{w}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) CO_2 + \left(\frac{w}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 + cNH_3$$

Here, (w, a, b, and c) are constants and their values are determined by the normalized mole ratio suggested by (Salami et al., 2011). Normalized mole ratio can be found as under:

The ultimate analysis of municipal solid waste of Lahore city (Azam et al., 2020)

Components	% C	%N	%H	%O	%S	%Ash	%Moisture
Biodegradable	62.5	0.4	8.0	28.8	0.1	9.6	4.0
Textile	58.4	0.6	4.9	35.7	0.16	5.0	2.9
Nylon plastic bags	78.7	0.12	12.4	8.7	0.02	5.5	0.1
Paper	50.5	0.22	6.4	42.3	0.55	18.8	3.4
Pet bottles	62.0	0.05	4.1	34	0.01	0.2	ND
Average	62.42	0.278	7.16	29.9	0.168	7.76	2.6

The normalize mole ratio. by Salami et al. (2011)

Element	Mass (kg)	Kg/mole	Moles	Normalization	Mole ratios Nitrogen = 1
Carbon (w)	62.42	12.01	5.197	5.197/0.0198	262.14
Hydrogen (a)	7.16 + 0.29= 7.45	1.01	7.376	7.376/0.0198	372.52
Oxygen (b)	29.9 + 2.31 = 32.21	16.00	2.013	2.013/0.0198	101.67
Nitrogen (c)	0.278	14.01	0.0198	0.0198/0.0198	1.00

Converting moisture content in organic portion of MSW to hydrogen and oxygen

Hydrogen = $\frac{\text{Atomic number} \times \text{moisture content}}{\text{molecular mass} \times 1}$

Hydrogen = $\frac{2 \times 2.6}{18 \times 1}$ = 0.29

Oxygen = $\frac{\text{Atomic number} \times \text{moisture content}}{\text{molecular mass} \times 1}$

Oxygen = $\frac{16 \times 2.6}{18 \times 1}$ = 2.31

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

$S_{CH_4} = 22400 \times (\frac{262.4/2+372.52/8-101.66/4-3(1)/8}{12(262.4)+372.52+16(101.66)+14(1)})$ = 659.5 Nm^3 CH4/ton

$MW_{OF}(AD) = MW_G(t) \times f(AD) \times D_F$

$MW_{OF}(AD)$ = 3289336.12 × 0.95 × 0.56 = 1749926.815

$\mathbf{CH_4(AD) = F_C \times MW_{OF}(AD) \times S_{CH_4}}$

$CH_{4\,(AD)} = 0.85 \times 1749926.815 \times 659.5 = 980965224.2\ m^3/year$

3) Calculation of electricity Production from AD and LFG technology for 2021

$\mathbf{E_{P(AD)\,(GWh)} = \frac{(CH_{4(AD)} \times E_{ff} \times LHV_{CH_4} \times CF)}{3.6}}$

$E_{P(AD)\,(GWh)} = \frac{980965224.2 \times 0.35 \times 37.2 \times 0.85)}{3600000}$ = 3015.6 GWh

$\mathbf{E_{P(LFGR)} = \frac{(CH_{4(LFG)} \times E_{ff} \times LHV_{CH_4} \times \lambda \times (1 - f_{ox}) \times CF)}{3600000}}$

$E_{P(LFGR)} = \frac{(5827479.62 \times 0.35 \times 37.2 \times 0.75 \times (1 - 0.10) \times 0.85)}{3600000}$ = 12.1 GWh

4) **Calculation of number of well required in estimation of investment cost in LFG technology**

Volume of waste

Total MSW generated = 144501024.4 tons

Waste goes to LF = 0.741 * 144501024.4 = 107176409.8 tons

(AS: density of MSW = 0.344 m^3/ton)

volume of this waste = (107176409.8 tons) / (0.344 m^3/ton) = 311559330.8 m^3

(To covert volume into ft^3 from m^3 , multiply by 35.315)

volume of this waste (ft^3) = 11002613931.17

volume of Landfill

volume of landfill (V) = L * B * H ………….1

Area (ft^2) = L * B   ……………………………. 2

By equation 1 and 2, area can be found

Area (L * B) (ft^2) = V / H

(As H is kept constant i.e 49)

Area (L * B) (ft^2) = 11002613931.17 / 49 = 224543141.4 ft^2

(To covert area in ft^2 to acres, divide by 43560)

Area (L * B) (acres) = 224543141.4 ft^2/ 43560 = 5154.1 acres

(As 1 acre requires 1 well, 5154.1 acres need 5154.1 wells) (He et al., 2017)

Number of well = 5154.1

5) **Displacement of diesel with equivalent of biogas (methane)**

$D_d(i) = FE_d \times E_P(i)$

$D_d(AD) = 0.33$ L/kWh $\times$ 132477978700 KWh = 43717732971 L = 43717.7 megaliter

$D_d(LFG) = 0.33$ L/kWh $\times$ 3458967430 KWh = 1141459252 L = 1141.4 megaliter

6) **Avoided CO_2 emissions due to displacement of diesel by biogas (methane).**

$A_C(i) = D_d(i) \times S_{EF}$

$A_C(AD) = 43717.7$ megaliter $\times$ 2.7 kg CO_2 / liter = 118037.8 ktons

$A_C(LFG) = 1141.4$ megaliter $\times$ 2.7 kg CO_2 / liter = 3081.78 ktons