UNIVERSITY OF MINES AND TECHNOLOGY (UMaT),

TARKWA

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

MUNICIPAL SOLID WASTE INCINERATION WITH ADVANCED EMISSIONS TREATMENT: GHANA CASE STUDY

BY

NOAH YAKAH

OCTOBER, 2023

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A PhD THESIS ENTITLED

MUNICIPAL SOLID WASTE INCINERATION WITH ADVANCED EMISSIONS TREATMENT: GHANA CASE STUDY

BY

NOAH YAKAH

SUBMITTED IN FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING

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OCTOBER, 2023

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DECLARATION

I declare that this thesis is my own work. It is being submitted for the degree of Doctor of Philosophy in Mechanical Engineering in the University of Mines and Technology (UMaT), Tarkwa. It has not been submitted for any degree or examination in any other University.

………………………………

(Signature of candidate)

……… day of ………. (year) ………….

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ABSTRACT

The annual solid waste generation worldwide is estimated to be 2.01 billion tonnes, however, this is expected to increase to about 3.4 billion tonnes by the year 2050. Again, the estimated per capita waste generation in Ghana per day is 0.47 kg, which translates to over 5 million tonnes of Municipal Solid Waste (MSW) generation annually. The disposal and management of this huge amounts of MSW generation has been challenging globally. In Ghana this is evident with the creation of unsanitary open dumpsites scattered across most communities throughout the country. The indiscriminate dumping of MSW has been attributed to cause flooding in most areas in the country. In fact, the use of waste incineration is a matured waste to energy technology which has become attractive for the disposal and management of MSW. Meanwhile, Ghana has been struggling to meet the electricity demand in the country. The electricity generation capacities of waste incineration facilities in the USA is about 2700 MW, 1925 MW in Germany, 925 MW in the UK, and 876 MW in Sweden. Major drawbacks with this technology include its high cost, and the release of huge volumes of emissions (including acidic gases), which may be detrimental to the environment. Due to the heterogenous composition of MSW as fuel, a simple import of the waste incineration technology to different locations are not usually successful, as such there is the need to perform a techno-economic assessment of the proposed waste incineration facility to be adopted in Ghana and improve on its emissions treatment. The technical assessment carried out in this study involves the determination of the amount of electricity that can be generated in proposed waste incineration facilities. Again, various models of the proposed waste incineration plant were developed and simulated using Aspen Plus® software to assess the performance of various particulate matter separation devices, as well as cleaning acidic gases from the flue gas streams using wet scrubbing and subsequently treating the generated wastewater using membrane distillation. The economic assessment carried out involves determining key economic indicators; the Net Present Value (NPV), and Levelized Cost of Energy (LCOE) for the proposed waste incineration facilities. Results indicate that a total of about 400 MW of electricity can be generated from the total MSW generated in Ghana annually, which can meet the electricity demand of about 8 million inhabitants in the country. The membrane distillation incorporated in the treatment of wastewater produced in the wet scrubbing during acidic gas cleaning had cleaning efficiencies of over 99 % and 95% for sulphuric and hydrochloric acids respectively. The NPV for a proposed 35 MW waste incineration

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facility was US$ 166,410,969.24 with a LCOE of US$ 0.19/kWh. It can be concluded that waste incineration facilities are not economically viable ventures in Ghana, and its implementation would therefore need government support in the form of subsidies and tax rebates.

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DEDICATION

This thesis is dedicated to my dear wife, Matilda Yeboah-Asiamah, and children, Colette Patience Yakah, Jesse Dela Yakah, and Padmore Victor Selase Yakah. I thank you all for your unflinching support throughout my PhD studies.

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I wish to thank God almighty for giving me the strength to come this far. These years of studies combined with teaching in the university has not been an easy one. Sometimes, the motivation to continue was lacking, but by His grace, I have been able to go through it all. The least I can say is thank you God.

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Special thanks to my sister and godmother, the late Prisca Bediako Puni, I thank God for bringing such a wonderful soul to be part of my life, how I wished you were alive to celebrate with me this milestone. But as we always say, God knows best. Maa Prisca continue to rest in peace till we meet again in the life after death.

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NOMENCLATURE

ACI	Activated Carbon Injection
AGMD	Air Gap Membrane Distillation
APCs	Air Pollution Controls
CHP	Combined Heat and Power
DCMD	Direct Contact Membrane Distillation
ESPs	Electrostatic Precipitators
FGD	Flue Gas Desulphurization
GOR	Gained Output Ratio
IWM	Integrated Waste Management
LCOE	Levelized Cost of Energy
MD	Membrane Distillation
MFCs	Microbial Fuel Cells
MGMD	Material Gas Membrane Distillation
MSW	Municipal Solid Waste
NPV	Net Present Value
OMD	Osmotic Membrane Distillation
PM	Particulate Matter
SEC	Specific Energy Consumption
SGMD	Sweeping Gas Membrane Distillation
TE	Thermal Efficiency
TSGMD	Thermostatic Sweeping Gas Membrane Distillation
UV	Ultraviolet
US-EPA	United States Environmental Protection Agency
VMD	Vacuum Membrane Distillation
WtE	Waste to Energy

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Units

kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
t/d	tonnes per day

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CHAPTER 1

INTRODUCTION

1.1 Background

According to a report from the World Bank (Kaza *et. al.*, 2018), the global annual generation of Municipal Solid Waste (MSW) is approximately 2.01 billion tonnes, and this is projected to rise to around 3.4 billion tonnes by 2050. The World Energy Resource Council (World Energy Council, 2016) has also projected that Africa's per capita urban MSW generation (measured in kg/day) is currently 0.65 and is expected to steadily increase to about 0.85 by 2025. This increase in waste generation is attributed to factors like population growth, industrialisation, improved living standards, and urbanisation (Solheimslid *et. al.*, 2015; Ni *et. al*., 2006; Patwa *et. al*., 2020; Han *et. al*., 2018).

Within the European Union (EU), the Waste Framework Directive introduced the "Waste Hierarchy", which prioritizes waste prevention as the foremost strategy, followed by reuse, recycling, resource recovery, and disposal in that order. This directive aims to promote sustainable waste management practices, minimise waste generation, and drive the shift towards a circular economy within the EU. Waste-to-Energy (WtE) technology, specifically waste incineration with energy recovery is recognised as a sustainable method of waste disposal. This technology is considered mature and suitable for managing MSW in developed countries (Dong *et. al*., 2018). Notably, the USA has approximately 77 waste incineration facilities (Executive Summary, 2020), the European Union operates around 492 (Waste-to-Energy Plants in Europe, 2015), and Japan runs about 1900 such facilities (Tan *et. al*., 2015). These developed nations favour waste incineration facilities due to its ability to reduce landfill waste and recover valuable energy in the form of electricity and heat.

In recent years, there has been a growing interest in using WtE technologies in developing nations like Nigeria, Brazil, Pakistan Indonesia, and Bangladesh as means of waste management and energy generation (Lino and Ismail, 2018; Mia *et. al*., 2018; Starostina *et. al*., 2018).

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1.2 Problem Statement

A research study conducted by Mieza *et. al*., (2015) estimated that the daily per capita solid waste generation in Ghana is approximately 0.47 kg per person. This translates to a total daily solid waste generation of over 14,000 tonnes in the country. Given the significant volume of daily waste produced, it is imperative to implement sustainable initiatives with minimal environmental impact for waste disposal and management.

Globally, managing the substantial amounts of MSW has posed considerable challenges. In Ghana, this issue has proven to be a recurring problem for successive governments, evident through the establishment of open landfill sites in numerous communities, particularly urban areas throughout the nation. Global Waste Management Outlook (2015) highlighted that the obstruction of drainage systems by indiscriminately disposed solid waste is a leading cause of flooding in Ghana, particularly in Accra, the capital city. In 2011 alone, flooding in Accra resulted in tragic consequences, including the loss of fourteen lives, displacement of about 17,000 individuals, and impact on approximately 43,000 people (Global Waste Management Outlook, 2015). Moreover, infrastructure such bridges, roads, and waterways suffered damage. The recurring nature of flooding during rainy seasons has transformed into a persistent issue, exacerbated by improper waste disposal. The resultant environmental problems encompass air pollution, water quality degradation, and toxicity issues, collectively posing threats to both human health and the environment. The proper management of solid waste has emerged as a paramount challenge for the current generation, and without effective measures, this challenge is likely to persist.

Concurrently, Ghana has grappled with meeting its energy demands, largely due to a shortfall in electricity generation. Consequently, the Electricity Company of Ghana has resorted to intermittent load shedding to manage the situation. Fossil fuels, constituting 61 % of total electricity generation, predominantly drive the energy mix in the country through various thermal power plants operated by the Volta River Authority and independent power producers (Energy Commission of Ghana, 2016). In light of these circumstances, the question arises: Can energy recovery from waste incineration facilities contribute to Ghana’s energy mix, thus diversifying the conventional methods of energy generation?

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Considering the advancements achieved in managing and disposing MSW through waste incineration facilities in developed nations, could a developing country like Ghana adopt this technology? It is important to note that MSW, when used as fuel, differs significantly from homogeneous fossil fuels like coal, making direct implementation of WtE technologies at different locations challenging. This difficulty stems from the varying composition of MSW across different global locations, influenced by factors such as geographical region, climate conditions, consumption patterns, and seasonal fluctuations (Maisarah et. al., 2018; Moya *et. al*., 2017).

Prior research (Acheampong *et. al.,* 2019; Akolgo *et. al.,* 2018; Danquah *et. al.,* 2018; Duku *et. al.,* 2011; Gomaa *et. al.,* 2020; Gyamfi *et. al.,* 2015; Kemausuor *et. al.,* 2014; Ofori-Boateng *et. al.,* 2012; Mohammed *et. al.,* 2013; Ulrike *et. al.,* 2017) has investigated and confirmed the significant potential for energy generation from waste in Ghana. While these studies explored both thermochemical and biological conversion methods within WtE technologies, the thermochemical methods focused specifically on gasification or pyrolysis.

While waste incineration has proven advantageous in developed nations, reducing MSW mass by up to 75 % and volume by up to 95 % (The Worldbank, 1999) and contributing to electricity generation, there are associated drawbacks. The combustion of MSW in incineration plants can lead to the generation of toxic gases. The composition of these gases depends on the specific fuel being burned. Common acidic gases produced in conventional waste incineration include hydrogen chloride (HCl), sulphur dioxide (SO_2), and hydrogen fluoride (HF). The release of these acidic gases into the environment from waste incineration facilities can have harmful effects (Mohajan, 2019), prompting environmental protection agencies to establish strict limits on their emissions. Various technologies are considered for mitigating emissions from waste incineration, such as wet, semi-dry, and dry scrubbing. Flue gas desulphurization (FGD) is a critical technique used in power plants and industrial settings to address the emission of these acidic gases. In waste incinerators, FGD systems play a pivotal role in removing or converting these harmful acidic gases, which are significant contributors to acid rain, through various chemical processes.

Absorption and adsorption represent two separate processes employed to cleanse flue gas streams emanating from waste incinerators. These processes are categorized into non-

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regenerative or regenerative methods. The non-regenerative techniques encompass dry, semi-dry, and wet methods (Neuwahl *et. al.*, 2019; Johnke, 2001). Wet scrubbing, often termed wet flue gas desulphurization, stands as a commonly adopted approach for eliminating acidic gases. In wet scrubbing, acidic gases are absorbed into a liquid absorbent, typically an alkaline solution. This solution, like sodium hydroxide or lime, subsequently reacts with the acidic gases to yield neutral salts. Among these, the limestone wet FGD method is prominently utilized for purifying acidic gases in flue gas streams from conventional thermal power plants (Carletti *et. al.*, 2013). Lecomte *et. al*. (2017) underline that this method can achieve removal efficiencies up to 99 %. Despite the manifold benefits associated with the wet FGD technique, a primary drawback involves wastewater generation, which amplifies the intricacy and expense of this process. The wastewater produced during wet FGD mandates treatment before reutilization or environmentally safe disposal.

Several wastewater treatment approaches are implemented for diverse wastewater types. Membrane separation methods, including microfiltration, ultrafiltration, and Reverse Osmosis (RO), are commonly employed. Notably, RO is widely favoured, though it has shortcomings like elevated electricity demand for achieving requisite pressures, thereby affecting long-term membrane performance (Noor *et. al.*, 2020). This underscores the necessity to explore alternative membrane separation methods.

Membrane Distillation (MD), a promising innovative technology, relies on porous hydrophobic membranes that permit solely water molecules to traverse. MD is extensively applied in desalinating seawater and brackish water (Alkhudhiri *et. al.*, 2012; Camacho *et. al.*, 2013; Qtaishat and Banat, 2013; Rahaoui *et. al.*, 2013), treating radioactive-laden wastewater (Liu and Wang, 2013; Korolkov *et. al.*, 2019), and addressing oily wastewater from industries (Ricceri *et. al.*, 2019; Tavakkoli *et. al.*, 2020; Said *et. al.*, 2020). However, its use in treating flue gas condensate has been relatively limited. A study (Chuanfeng and Martin, 2005) examined MD within the context of combined heat and power (CHP) plants in Sweden. Subsequently, a pilot unit was installed at the Vattenfall Idbacken CHP plant (a biofuel fired plant) from 2006 to 2007 (Kullab, 2011). Later, an ensuing investigation focused on extracting water from flue gas condensate in cogeneration plants fuelled by MSW. This study utilized MD and encompassed both laboratory and pilot-scale air gas MD modules. The research also included a techno-economic assessment. These mentioned

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inquiries illustrated that MD achieves comparable or superior separation efficiency compared to RO but at a higher specific cost. The presence of low-grade heat constrained the MD system's capacity to approximately 100 m^3/hr. However, their research centred on cogeneration plants, which provide both heat and electricity, and not waste incineration facilities operating on condensing mode, where electricity is the sole energy output as would be the case if it is to be adopted in a tropical country like Ghana.

1.3 Objectives of the Research

The aim of this research work is to propose waste incineration with energy recovery as a sustainable WtE technology that can improve on MSW management in Ghana and evaluate the thermal performance of an incorporated membrane distillation for enhanced emissions treatment. The specific objectives are:

i. To review the current state-of-the-art in waste to energy technologies with particular emphasis on waste incineration technology.
ii. To perform techno-economic assessment of a waste incineration facility with energy recovery plant proposed for use in Ghana.
iii. To incorporate a membrane distillation into the proposed waste incineration plant and evaluate its thermal performance.

1.4 Research Questions

This thesis will be based on the following research questions:

i. What are the merits and demerits of waste to energy technologies employed in nations worldwide?
ii. What are the challenges with the use of waste incineration with energy recovery in the disposal and management of MSW?
iii. How are the challenges with the use of waste incineration facilities addressed in nations where these plants are operating?
iv. What are the performances of emission controls that can be incorporated into the waste incineration plant?

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1.5 Methodology

The research methods used include:

i. Field visits (visits to the landfill sites in Kumasi operated by the Kumasi metropolitan assembly, the solid waste treatment plant in Adjen Kotoku operated by Accra Compost and Recycle Plant (ACARP), and other smaller landfill sites scattered around most communities in Ashanti, Greater and Western Regions of Ghana).

ii. Modelling and simulation of a waste incineration plant using Aspen Plus® software (version 11).

1.6 Limitation of the Research

This research is limited to review of literature, modelling, and simulation.

1.7 Organisation of Thesis

This thesis is organised into five main chapters, and the details of the various chapters are as follows;

i. Chapter One presents the introduction, which encompasses the background to the study, problem statement, objectives of the research, research questions that the thesis seeks to answer, the methods employed, the limitation of the research, and an outline of the thesis report.

ii. Chapter Two presents literature review. Various literature relevant to the theme of this research work was reviewed. The topics reviewed in this chapter includes, an overview of waste, waste management practices, current MSW management in Ghana, classification of WtE technologies, status of waste incineration facilities worldwide, state of WtE technology in Ghana, selection of an optimum WtE technology, choice of WtE technology, current status of electricity generation in Ghana, CO_2 emissions from the electricity power sector, waste incineration technology, emission control strategies in waste incineration facilities, acidic gas cleaning in flue gases, particulate matter and its separation, dioxins/furans

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formation and control, wastewater treatment and membrane distillation, technical and economic assessment of a waste incineration facility, and a brief geography and population distribution of Ghana.

iii. Chapter Three presents the methods that were used for conducting this research work. The relations used in performing the techno-economic assessment of proposed waste incineration facilities for use in Ghana are presented. Methods used to determine CO_2 emissions from thermal power plants operating in the country are presented, and finally the various models simulated for this research work are also described explicitly in this chapter.

iv. Chapter Four presents the results and discussions for this research work. Results presented in this chapter includes results from the techno-economic assessment of waste incineration facilities proposed for use in Ghana, and the results from the simulation of various models of the proposed waste incineration facility. An analysis performed on the incorporation of waste incineration into the electricity generation mix of Ghana is also presented. Finally results from parametric studies performed on PM separation devices and the MD system are also presented in this chapter.

v. Chapter Five presents the conclusion and recommendations for future work in the research area.

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CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter reviews various literature on topics in line with achieving the aim and objectives of this research work. Literature reviews covered in this chapter are an overview of waste, waste management practices, current MSW management in Ghana, classification of WtE technologies, status of waste incineration facilities worldwide, state of WtE technology in Ghana, selection of an optimum WtE technology, choice of WtE technology, current status of electricity generation in Ghana, CO_2 emissions from the electricity power sector, waste incineration technology, emission control strategies in waste incineration facilities, acidic gas cleaning in flue gases, particulate matter and its separation, dioxins/furans formation and control, wastewater treatment and membrane distillation, technical and economic assessment of a waste incineration facility, and a brief geography and population distribution of Ghana.

2.2 Waste

There are numerous definitions offered by dictionaries on the term "waste". An important but simple definition of this term from the Merriam-Webster's Dictionary include: "refuse from places of human or animal habitation, damaged, defective, or superfluous material produced by a manufacturing process".

Waste is also defined as anything which does not have any use for the holder. This definition of waste does not, however, include sewage effluent, radioactive waste, and emissions into the atmosphere. The issue of waste disposal and its management is one that has plagued nations worldwide, regardless of their social-economic standing or reputation.

According to the World Bank (Kaza *et. al.*, 2018), although there are significant variations in waste generation by region, waste generation can be viewed as a function of wealth. The report estimated that in 2018, global waste generation stood at 2.01 billion tonnes per year. However, this is expected to increase to 3.4 billion tonnes per annum by the year 2050. Generally, it can also be observed that areas with higher rates of urbanisation and economic development tend to have a greater amount of solid waste generation compared to areas with lower economic development (Hoornweg *et. al.*, 2012). This trend can

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clearly be observed in Figure 2.1, which illustrates the percentage of waste generated by low-, middle-, upper middle-, and high-income countries in the world.

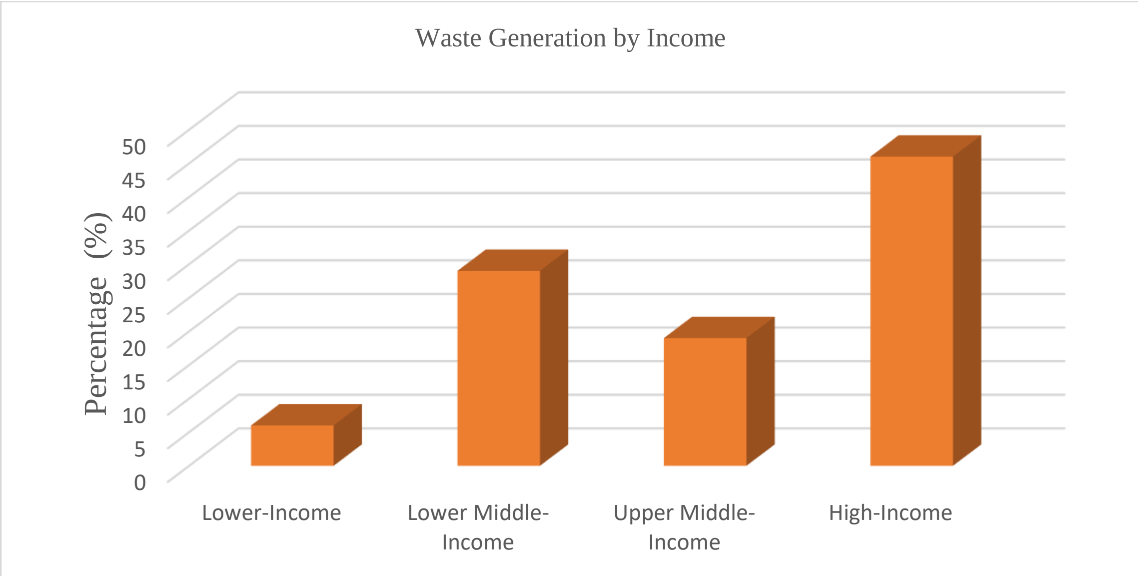

Figure 2.1 Waste Generation by Income

(Source: Hoornweg *et. al.*, 2012)

Local climate and public habits are also factors that influence waste generation rates (McAllister, 2015). Tchobanglous G. *et al* 2002 identified seven key issues that need to be considered in discussing solid waste management. These seven key issues are:

i. Swelling amounts of waste
ii. Waste that are not usually reported in nationwide MSW sums
iii. Non-existence of unblemished definitions that are applicable to solid waste management words and roles.
iv. The absence of quality data on MSW
v. Necessity for unblemished roles and leadership in usually state, federal and some cases local government.
vi. Additionally, the need for uniform and predictable enforcement roles and ethics and
vii. Resolution of interstate, intercounty waste issues for MSW and its components.

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2.2.1 Waste classification

There are various ways by which waste can be classified. Waste can broadly be categorised into two groups, organic and inorganic. Organic waste is biodegradable waste, and this is waste that basically comes from plants, animals, or food. Inorganic waste, on the other hand, are non-biodegradable waste and these include plastics, glass, papers, and metals (Ana Pérez-Gimeno *et. al*., 2019).

Waste can also be classified either as biodegradable or non-biodegradable. Biodegradable waste (also referred to as putrescible waste) are waste that are generated from sources like plants, or animal sources and are degradable or can be broken down by organisms, examples are food leftovers, faecal matter, trimmings from lawn mowing, etc. Non-biodegradable waste (also referred to as imputrescible waste), are waste that are usually from materials that are not broken down naturally by organisms, examples include metals, leather, plastics, papers, etc. (Geevarghese *et. al*., 2022).

Waste can also be classified as either being combustible or non-combustible waste when considering incineration of the waste. Combustible wastes are usually organic waste, and some other inorganic waste that are burnable, examples include papers, textiles, plastics, etc., whereas, non-combustible wastes include glass, metals, ceramics, etc., and these waste cannot be burned.

2.2.2 Municipal Solid Waste and its Characterization

The definition of Municipal Solid Waste (MSW) varies from one literature to the other. However, according to EU 2008, MSW can defined as

- "Mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste batteries and accumulators, electrical and electronic equipment, mattresses, and furniture" and
- "Mixed waste and separately collected waste from other waste sources, where such waste is similar in nature and composition to waste from households".

Also, according to the United States National Research Council (National Research Council, 2000), MSW is defined as the "solid portion of waste (not classified as hazardous or toxic) generated by households, commercial establishments, public, and private

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institutions, government agencies and other sources". This stream of waste consists of food and yard waste, and a plethora of durable and non-durable products, as well as packaging.

MSW is also defined as non-homogeneous materials that are generated through anthropogenic activities by households as well as in commercial places within a municipality. This comprises waste like plastic, leather, metals, glass as well as waste that are generated from food industries (like hostels, restaurant, hotels, and households), and others which are inorganic (Daura, 2016).

MSW, however, excludes waste such as automobile bodies, municipal sludges, non-hazardous industrial process waste, combustion ash, construction, and demolition waste. The amount of MSW generation can basically be viewed as the sum of waste collected and disposed of on behalf of the municipal authorities.

Waste composition is considered paramount in the identification of the best practice to be adopted for its disposal and management. A study (Jin *et. al*., 2006) indicates that MSW composition is largely influenced by factors such as cultural conditions, lifestyles, literacy rates, economic status, food habits as well as geographical and climate conditions prevailing at a location under consideration. For over five decades, data gathered by the United States Environmental Protection Agency (United States Environmental Protection Agency, 2022) shows that paper and paper board make up about twenty five percent of the total MSW generated for a period spanning from 1960 to 2018. Figure 2.2 shows estimated values for the composition of MSW generated in the USA in 2018 alone. Clearly, it can be observed that paper, and paper board account for almost a quarter of the total of 292.4 million tonnes of MSW that was generated in the USA.

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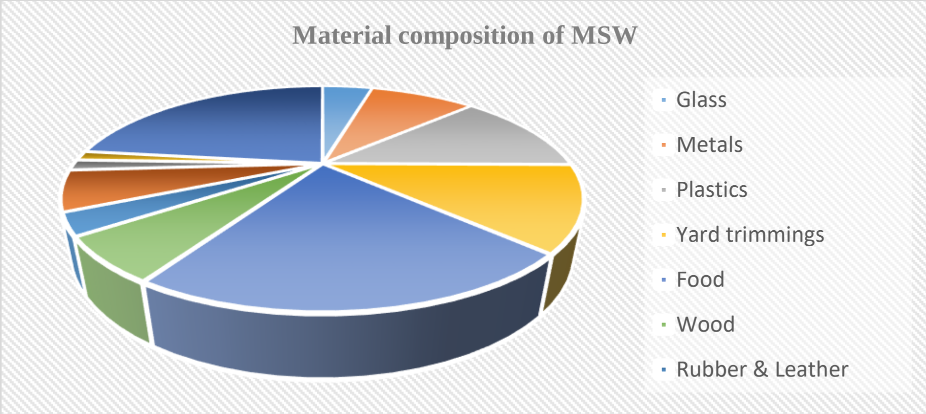

Figure 2.2 Material Composition of MSW in the USA for 2018

(Source: United States Environmental Protection Agency, 2022)

2.2.3 Waste Composition in Ghana

The composition of MSW in Ghana just like how it is done in other parts of the world can also be segregated into various composition. A study (Mieza *et. al*., 2015) indicates the composition of MSW in Ghana as;

i. Organics - which consist of food waste, wood, yard waste, and animal droppings
ii. Paper - cardboards, newsprints, tissue, and office papers
iii. Plastics – polyethylene terephthalate, low density polyethylene, high density polyethylene, polyvinyl chloride, polystyrene, polypropylene, and other plastics
iv. Metals – scrap and cans/tins
v. Glass – both coloured and plain ones
vi. Rubber and Leather
vii. Textiles
viii. Inert (fine organics, ash, and sand)
ix. Miscellaneous (paints, demolishing and construction waste, batteries, any other fraction that do not fall into the mentioned categories).

The study concluded that the composition of MSW generated in Ghana is dominated by organics (constituting 61 %), followed by plastics (constituting 14 %), and the rest are, 5 % paper, 3 % metal, 3 % glass, 1 % rubber and leather, 2 % textiles, 6 % inert and 5 % miscellaneous. This is depicted in Figure 2.3.

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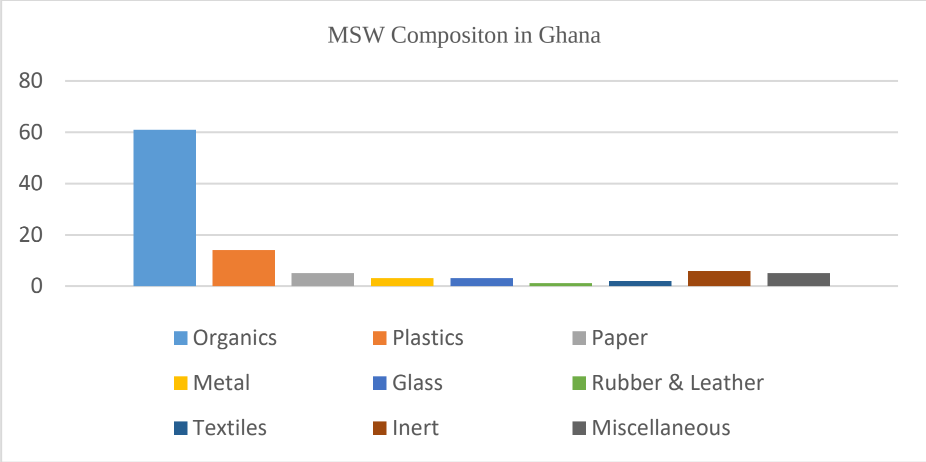

Figure 2.3 MSW Composition in Ghana

(Source: Mieza *et. al*., 2015)

2.2.4 Sources of MSW

Sources of MSW may differ from one area to another depending on the category of waste and the definition for the scope of waste that the municipal authorities oversee. However, a study (Hoornweg *et. al*., 2012) identified six main sources of MSW. These sources are residential, commercial, institutional, industrial, construction and demolition, and municipal services.

i. Residential – the report identified single and multifamily dwellings as a typical waste generator, and identified food waste, e-waste, paper, plastics, household hazardous waste, leather, glass, etc.
ii. Commercial – another source of MSW identified by the report is the solid waste from commercial sources. Under this category, markets, stores, hotels, restaurants, and office buildings are typical waste generators. Some of the types of solid waste identified include paper, cardboard, food waste, e-waste, etc.
iii. Institutional – schools, government buildings, airports, prisons, and hospitals (non-medical wastes) were identified as typical waste generators. The same types of solid waste listed under commercial sources were identified for institutional sources.
iv. Industrial – industrial source of MSW was also identified by the report. Typical waste generators under this source of MSW include construction sites, fabrications, chemical plants, light and heavy manufacturing, and

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power plants. Some types of solid waste given under this section include hazardous wastes, packaging, food wastes, housekeeping wastes, etc.

v. Construction and Demolition – solid wastes from construction and demolition sources also considered with new building sites, road maintenance, renovation sites and pulling down of buildings identified as typical construction and demolition waste generators. Some types of solid waste under this section include bricks, tiles, wood, steel, concrete, and dirt.

vi. Municipal services – under this category of MSW source, street cleaning, landscaping, recreational zones, water, and effluent treatment plants were identified as typical waste generators while landscape and tree trimmings and street sweepings, general waste from recreational areas and sludge were identified as other types of solid waste.

Commercial, institutional, and industrial sources are oftentimes grouped and constitute more than half of MSW. However, if the municipal authorities oversee the collection and disposal of the following waste, then they can also be classified as a source of MSW (Hoornweg *et. al*., 2012).

i. Process – refineries, power plants, chemical plants, processing and mineral extraction and processing constitute some typical waste generators while materials such as slag, tailings, industrial process waste and scrap materials are some examples of typical processed solid wastes.

ii. Medical waste – under this category of MSW source, hospitals, nursing homes and clinics were identified as typical waste generators while pharmaceutical waste, chemicals and sharp items were identified as typical solid waste.

iii. Agricultural – typical waste generators identified under this category include crops, diaries, orchards, feedlots, and farms while spoiled food waste, hazardous waste such as pesticides were identified as typical agricultural solid waste.

2.3 Waste Management Practices

As part of programmes to combat waste, many countries have developed strategies to mitigate against the escalating rates of MSW generation. In some literature, the disposal and management of waste is usually presented as integrated waste management (IWM)

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and according to Tchobanoglous G. *et al*., (2002) IWM is defined as "the selection and application of suitable techniques, technologies, and management programmes to achieve specific waste management objectives and goals". There are basically four strategies that are adopted by the US-EPA (Best Practices for Solid waste management, 2020), source reduction, recycling and composting, landfills, and Waste-to-Energy (WtE) technologies.

2.3.1 Source Reduction

This strategy of MSM management is focused on reducing either the volume and harmfulness of the waste generated and can be adopted by all and sundry. A more pragmatic approach to this strategy of waste management is to switch to reusing products and packaging (a typical example of such is the use of returnable bottles).

Consumers are usually encouraged to partake in source reduction by buying fewer products as possible or by using the products expeditiously (Tchobanoglous G. *et. al*., 2002). According to a study (Hezri *et. al*., 2010), while low-income countries have no structured programmes for source reduction, the situation nevertheless is different from high-income countries where a great deal of educational programmes are organised which emphasizes the necessity to reuse, reduce, and recycle waste (what has been nicknamed the 3R's of waste). Johnson B., (2013) describes source reduction as an immediate aid to the current environmental crisis. The study also added that, not only does source reduction addresses the core issues of waste problems but also takes into consideration the likelihood of environmental consequences as a result of population growth, with accompanying consumption and scarce resources that cannot satisfy the needs of mankind. Additionally, Tchobanglous G. *et al*., (2002) considered source reduction as the best practice at the process design phase of the production of any product. Johnson B., (2013) listed three practices that can be implemented to reduce waste, and these are, evaluate past consumption, to limit present and future consumption in terms of amount and size, decreasing activities that could lead to consumption.

i. Evaluate past consumption – this can be achieved by assessing the true use and need of everything, after which ones which are deemed unnecessary are pared down.
ii. To limit present and future consumption in terms of amount and size - this can be achieved by avoiding shopping activities so as to conserve valuable

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resources to make new things, and by making used items available to others. Areas that can be considered include home sizes, reducing packaging, personal effects, etc.

iii. Decreasing activities that may support or lead to consumption.

Source reduction is usually seen as the best approach and is encouraged by making sure the cost of the management of waste is fully internalised. The cost that needs to be internalised, for waste management, includes site, administrative, pickup and transport, construction, salary, and environmental monitoring controls (Tchobanglous G. *et. al*., 2002). Although source reduction is perceived to be an effective way of managing waste by making sure that the amount of waste generation is minimal, that cannot stop the generation of waste in the society. There is, therefore, the need to pursue other means of disposing and managing waste that would eventually be generated.

2.3.2 Recycling and Composting

Among the waste management practices, recycling is considered perhaps the most positively perceived and achievable strategy. Recycling returns a sustainable number of raw materials to the market by separating reusable products from the remainder of the municipal waste stream, thus saving limited resources to feed the industry. According to Tchobanglous G. *et. al*., (2002) recycling can improve the ash quality of incinerators and composting facilities, as well improve the facilities' efficiency by removing non-combustible materials, such as glass and metals. Recycling is applicable in the disposal and management of only the inorganic components of waste.

The biological decomposition of organic waste (such as food and plant materials) by either worm, fungi, bacteria, and other organisms usually under controlled aerobic conditions is referred to as composting. This method of waste management can be used in the treatment of only the organic components of MSW.

2.3.3 Landfills

The cheapest and widely used means of waste disposal worldwide and mostly in developing countries has been landfill (Agamuthu *et. al*., 2012). However, this traditional means of waste disposal has been a major environmental problem that pollutes the air,

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land, groundwater, and endangers human health (Georgieva *et. al*., 1999). Landfilling has also been found to be a major culprit to greenhouse gases. It has been estimated that landfills contribute about 5 % of greenhouse gases (methane (CH_4), Nitrogen oxide (N_2O), carbon dioxide (CO_2)) that depletes the ozone layer as well as causes climate change (Zhang *et. al*., 2019). Leachate from waste dumps contains huge amounts of dissolved fatty acids, methane, nitrate, calcium, phosphates, chloride, sodium, potassium, magnesium, and trace metals. The leachate from the waste dump in landfill sites is attributed to be a major cause of severe pollution in aquifers and causes serious eutrophication conditions predominately in surface water (Zhen Han, and Baoshan Cui, 2016).

2.3.4 WtE Technologies

There are a lot of definitions that are given to WtE technologies, and this can be very broad, since it encompasses those that are simple and others that are complex in design. WtE technologies can basically be defined as, all technologies that treat waste with the aim of energy recovery at the end of the process. The recovered energy from any WtE technology can be either electricity, heat, or fuels (in solid liquid, or gaseous form). The use of WtE technology has become the preferred choice in the disposal and management of waste in most industrialised nations, with several plants in operations.

2.4 Current MSW Management Practices in Ghana

In Ghana, it is approximated that MSW constitutes approximately 80 % of the total waste produced in the nation (Ofori-Boateng et. al., 2012). Likewise, in developing countries at large, it is estimated that over 90 % of the waste generated is disposed of improperly, either through open burning or unregulated landfill dumping (Ferronato *et. al*., 2019). The unregulated disposal of waste on streets, drains, and water bodies without proper collection measures has been linked to flooding and the propagation of diseases. Research by Abalo *et. al*., (2018), suggests that only 28 % of the waste generated in the main municipalities of Ghana undergoes proper collection, while the remainder is discarded as mentioned earlier. The individual waste generation in Ghana is estimated to be around 0.47 kg/person/day (Mieza *et. al*., 2015), leading to a daily total of over 14,000 tonnes of solid waste generated in the country. The waste collection process in Ghana has seen

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enhancements in recent times, thanks to the involvement of private individuals and businesses. These entities engage in activities such as gathering waste from households, institutions, and commercial establishments, subsequently depositing the collected waste in open landfill sites on the outskirts of towns, or sometimes in unauthorized areas like rivers and streams (Oduro-Kwarteng, 2010). Hence, there is a pressing need to establish sustainable initiatives aimed at effectively managing the generated MSW in the country.

2.5 Classification of WtE Technologies

WtE technologies can broadly be classified into two, namely, thermochemical, and biological conversion methods. Figure 2.4 is a flowchart of the various WtE technologies including the useful energy that can be derived from each technology.

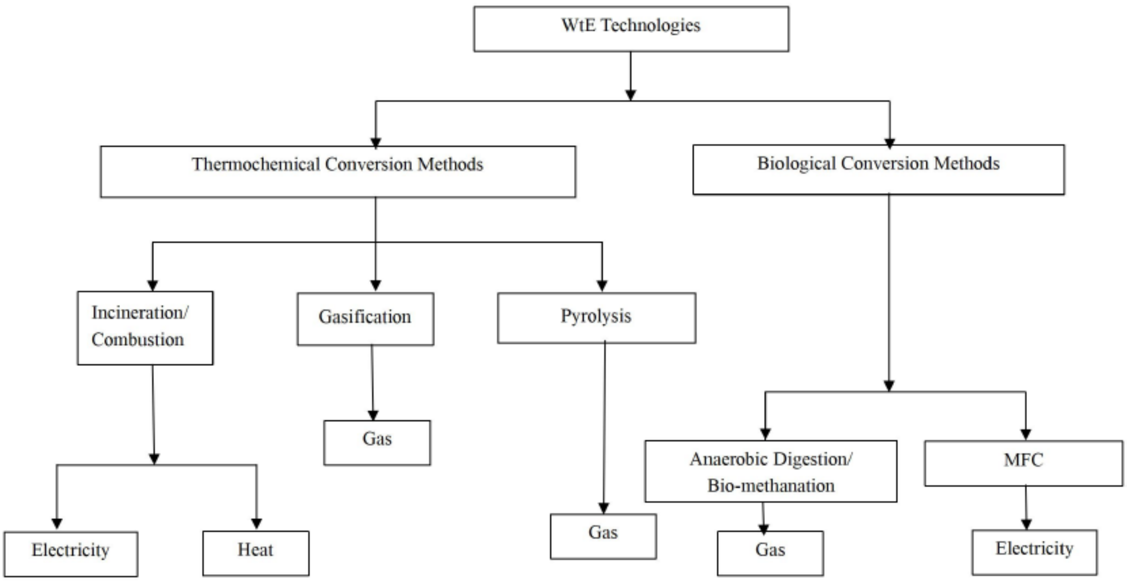

Figure 2.4 A Flowchart of the various WtE Technologies and their End Products

(Source: Executive Summary, 2020)

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2.5.1 Thermochemical Conversion Methods

The thermal conversion method of WtE technology is the application of heat and/or air (oxygen) in treating MSW to generate electricity and heat or both. Thermal conversion methods of the WtE technology process can be either exothermic or endothermic. Thermochemical conversion methods, relative to biological conversion methods, have demonstrated to be more efficient due their faster reaction rates, and larger reduction in the mass and volumes of the MSW (Rosen and Dincer, 1997).

Thermochemical conversion methods can be divided into waste combustion (also referred to as waste incineration), gasification, and pyrolysis. The distinction between the various types of thermochemical conversion methods depends on the degree of temperature and the amount of air (or oxygen) concentration.

Waste Combustion/Incineration

Waste combustion/incineration is a type of thermochemical conversion method of WtE technology where usually mixed MSW are burned in the presence of excess air or oxygen at temperatures between 800 °C and 1200 °C. Unlike earlier waste incineration facilities which had the sole aim of reducing the mass and volume of MSW that was sent to landfill sites, recent waste incineration facilities have systems incorporated to produce steam and subsequently for electricity generated.

Gasification

Gasification is a partial oxidation thermo-chemical conversion process at high temperature that is able to convert carbonaceous materials (e.g., coal, MSW…) into a combustible gas referred to as a synthetic gas (syngas). Most of the carbon and hydrogen in the feedstock used in gasification is converted into syngas comprising carbon monoxide (CO), CH_4, hydrogen (H_2), leaving behind a solid residue of inert ash and a char. In gasification, an external heat source is needed to maintain it operating temperatures at optimum levels. The process of gasification is, however, exothermic, although some amount of heat may be required to initiate the process and sustain it. The processed syngas can be used for a variety of applications (after cleaning). Figure 2.5 is a diagram showing a waste gasification plant.

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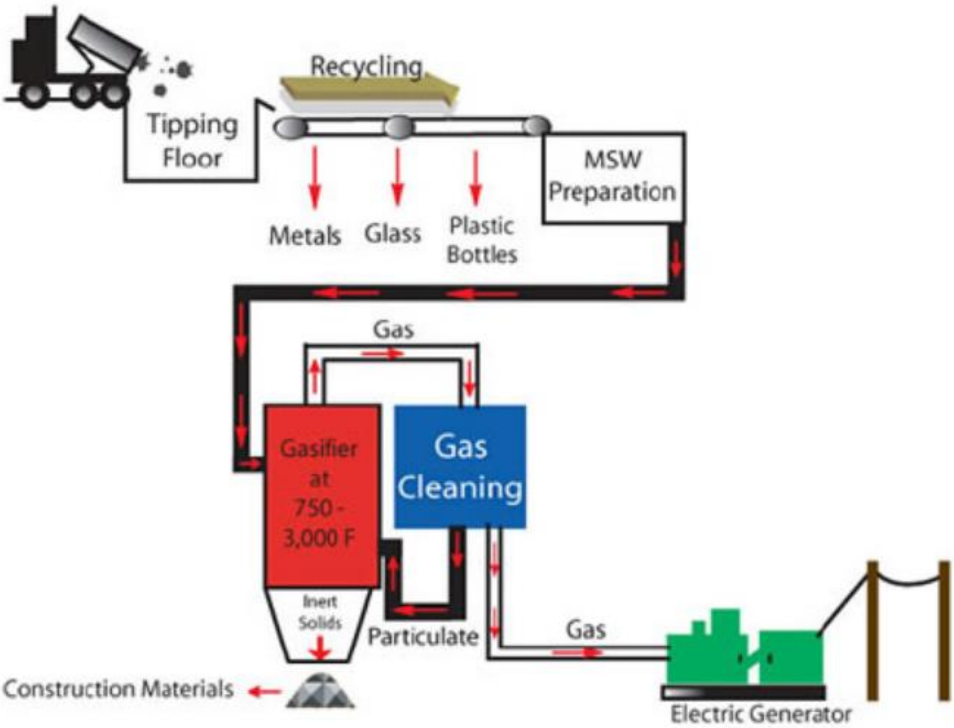

Figure 2.5 A Solid Waste Gasification Plant

(Source: Zafar, 2009)

The syngas derived from the process of gasification is usually combusted in internal combustion engines to produce heat and electricity. The syngas produced during gasification, may also be used to manufacture high-quality oils, additives, or synthetic natural gas (SNG) after it has been treated (Vineet *et. al.*, 2016).

Pyrolysis

Pyrolysis is the thermal decomposition of carbon-based materials at higher temperatures in the absence of oxygen. This process involves the change of the chemical composition of the feedstock (the waste in this case). Pyrolysis of organic compounds produces volatile materials (syngas), and a carbon-rich solid residue known in general as biochar and an oil, also known as bio-oil (Arun *et. al.*, 2023).

The amounts of valuable products from the pyrolysis process (CO, H_2, CH_4, and other hydrocarbons), and their proportion depends exclusively on the pyrolysis temperature and

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the rate of heating (Arun *et. al*., 2023). The bio-char is usually produced at temperatures below 450 °C, while the syngas produced are produced at temperatures above 800 °C, however, bio-oil is produced at relatively intermediate temperatures (Arun *et. al*., 2023).

In the processes of combustion and gasification, pyrolysis is considered as the first step (Arun *et. al*., 2023). An external heat source is required to maintain the temperature throughout the process of pyrolysis and as such, pyrolysis is an entirely endothermic process. A study estimated the net calorific value of the syngas produced during the process of pyrolysis to be between 13 and 20 MJ/Nm^3 (Velghe *et. al*., 2011). The syngas produced can be combusted in internal combustion engines for the generation of heat and electricity. However, the syngas is cleaned prior to being combusted in the internal combustion engines. It has also been reported that pyrolysis of plastic materials can produce liquid hydrocarbons, which can be distilled such that it has properties similar to petroleum-based products (Velghe *et. al*., 2011). Figure 2.6 shows the process of a solid waste pyrolysis.

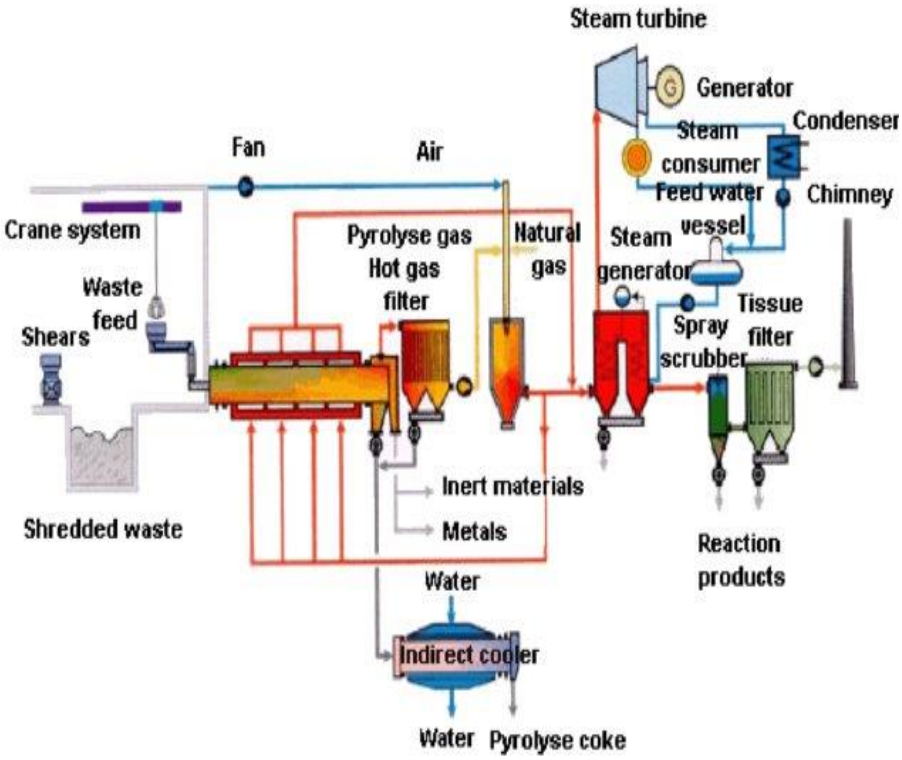

Figure 2.6 A Waste Pyrolysis Plant

(Source: Vatopoulos *et. al*., 2012)

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2.5.2 Biological Conversion Methods

Biological conversion methods of the WtE technology uses micro-organisms in carefully controlled conditions to convert MSW into biogas, consisting mainly of methane and carbon dioxide and stabilised residue known as digestate. Anaerobic digestion/Bio-methanation, and Microbial Fuel Cells (MFC) are all biological conversion methods of WtE technology.

Anaerobic Digestion/Bio-methanation

Anaerobic digestion/bio-methanation is a process in which organic matter is broken down by micro-organisms in the absence of oxygen, resulting in biogas, a methane-rich gas used as a fuel, and digestate, which is a nutrient-rich fertiliser. The operating time per cycle, or how long it takes for an anaerobic digestion plant to process organic waste, is usually 15 to 30 days (Final Report, 2003).

With a combined heat and power unit, the biogas, generated naturally in sealed tanks is used to generate renewable energy in the form of electricity or heat. The bio-fertiliser is pasteurised which can eliminate pathogens and can be applied twice a year to farmland, effectively replacing fossil-fuel-based fertilisers. This technology is commonly used in the treatment of wastewater but can also be employed in the treatment of organic waste ranging from households and industrial food waste to manures and biofuel crops.

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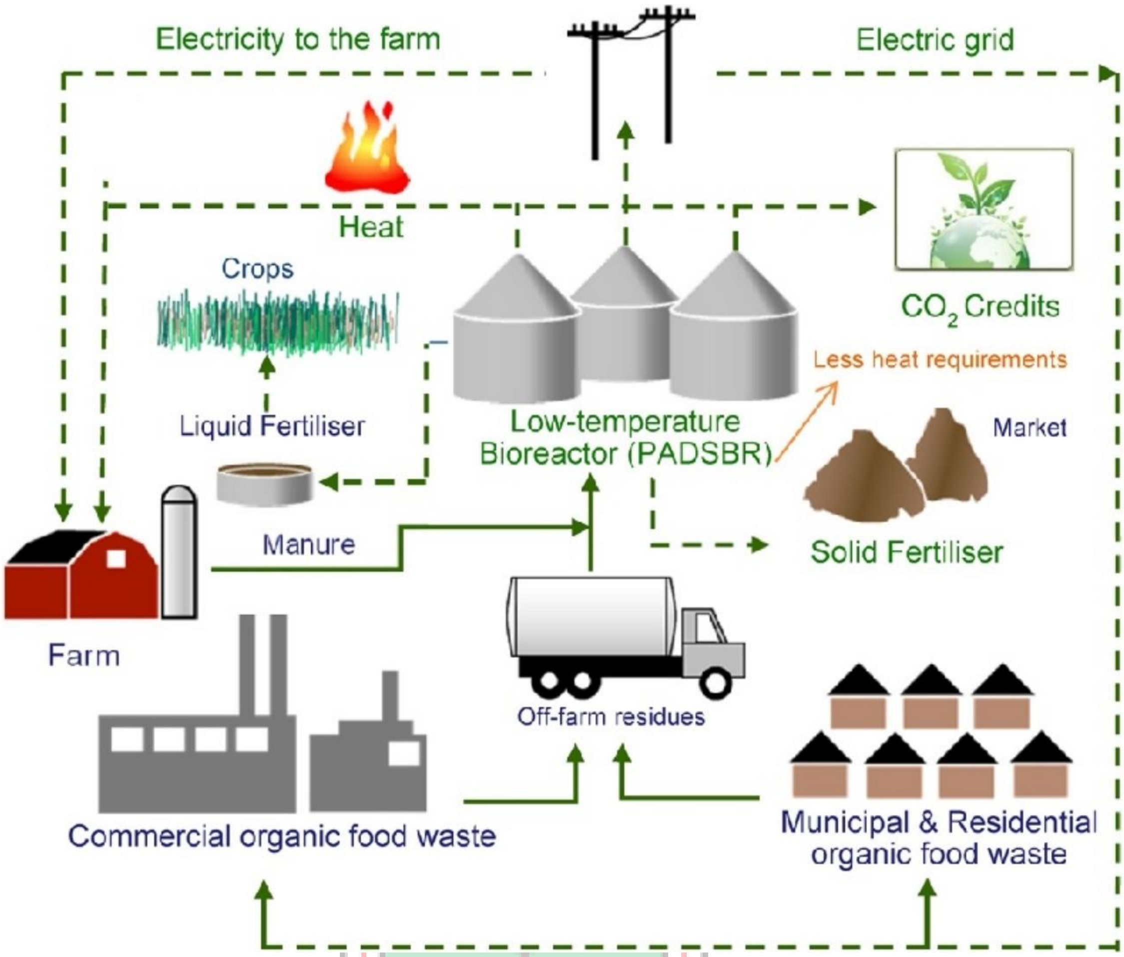

Figure 2.7 An Anaerobic Digestion Plant

(Source: Rajinikanth *et. al.*, 2017)

The steps involved in the anaerobic digestion process are hydrolysis (where hydrolytic enzymes break down complex polymers into basic amino acids, sugars, and fatty acids), Acidogenesis (breakdown of simple monomers into volatile fatty acids), Acetogenesis (products of acidogenesis are broken down into acetic acid) and finally, Methanogenesis (methane and carbon dioxide are produced). Figure 2.7 depicts a typical anaerobic digestion plant. These steps usually take place in reactors which are enclosed systems (referred to as digesters). Elango *et. al.*, 2007, estimates that 100 m^3 of biogas can be generated from a tonne of MSW.

Microbial Fuel Cell

A microbial fuel cell is a system that utilises microorganisms to transform chemical energy in organic compounds into electricity energy (Ruscalleda *et. al.*, 2011). Bio-

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cathode and/or bio-anodes are used to create these electrochemical cells and a membrane divides the anode (where oxidation takes place) and cathode compartments in most MFCs (where reduction takes place). In MFC, electrons which are produced during oxidation are directly transferred to an electrode or a redox mediator species. The electron flux is transferred from the anode to the cathode. Most MFCs oxidize an organic electron donor to produce CO_2, protons, and electrons. Other electron donors, such as hydrogen or sulphur compounds, have been identified (Ruscalleda *et. al*., 2011). The cathode reaction employs several electron acceptors, the most common of which is oxygen. Metal recovery by reduction, nitrate reduction, water to hydrogen, and sulphate reduction are among the other electron acceptors in investigated (Ruscalleda *et. al*., 2011). It can be applied in power generation, biosensors, and wastewater treatment. Figure 2.8 shows a diagram of a microbial fuel cell. Table 2.1 lists the advantages and disadvantages of the various WtE technologies.

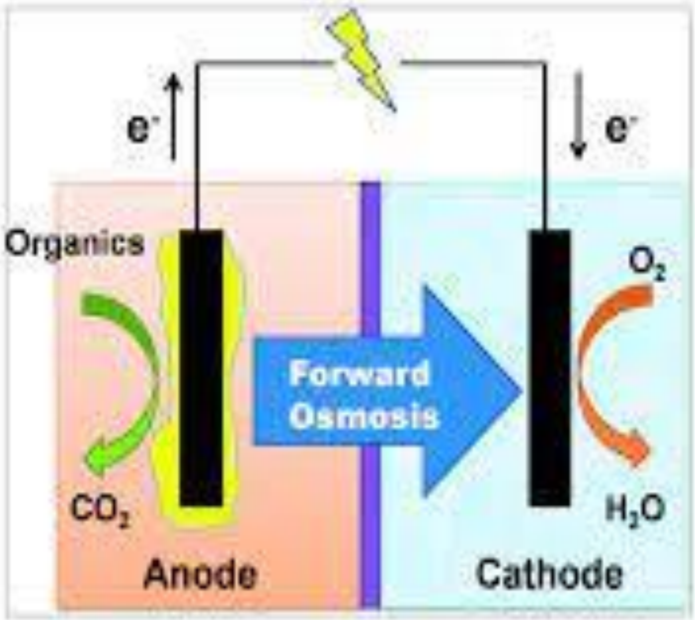

Figure 2.8 A Microbial Fuel Cell

(Source: Fei *et al*., 2011)

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Table 2.1 Advantages and Disadvantages of WtE Technologies

Technology	Advantages	Disadvantages
Waste Incineration	• Has a smaller installation area. • Has a lower noise and odour generation. • Waste incineration facilities can be built within the city thereby reducing the cost of transporting the waste. • Substantial reduction of mass and volume of MSW • Waste incineration can reduce pollution relative to landfill sites since it prevents the production of methane gases (methane is considered a major greenhouse gas).	• There is the need for vigorous flue gas treatment, which increases the cost of the technology. • Has a high maintenance and operational cost
Gasification	• Production of waste fuel gas/oil which be used for several purposes. • Substantial reduction of the volume of waste (up to 90%) • This technology is reliable and has seen more applications in chemical industries, refining and fertilisers. • It has been found be more efficient than waste incineration.	• Production of Tar • Technology immature, and inflexible with higher risk of failure • More suitable when used for large scale power plants employing Rankine cycle. • Reactions usually leads to corrosion of metal tubes. • Has a higher capital as well as operating costs.

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Table 2.1 Advantages and Disadvantages of WtE Technologies (Cont'd)

Pyrolysis	i. Production of higher quality fuel (bio-oil, bio-char, and syngas) ii. It can create jobs since members in the community can be involve in the collecting and sorting of solid waste materials that would be used in the pyrolysis facility. iii. It has a reduced flue gas treatment. iv. Higher energy recovery rate (estimated to be about up to 80%).	i. Pyrolysis processes involve complex thermal and chemical reactions that require precise control of operating conditions, such as temperature, pressure, and residence time. ii. Different types of feedstock have varying compositions and properties, which can affect the efficiency and quality of pyrolysis products. Some feedstocks may contain contaminants or high moisture content, which can have an adverse impact on the pyrolysis process and the quality of the resulting products. iii. Pyrolysis can release emissions, including Particulate Matter (PM), Volatile Organic Compounds (VOCs), and gases such as carbon monoxide and Nitrous Oxide (NOx). iv. The pyrolysis process requires significant amount of energy input to reach the necessary operating temperatures.

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Table 2.1 Advantages and Disadvantages of WtE Technologies (Cont'd)

Anaerobic digestion	i. It can treat a variety of organic waste materials, such as agricultural residues, food waste and sewage sludge. ii. The biogas produce during the process can replace fossil fuels, leading to a reduction in greenhouse emissions.	i. High capital cost. The implementation of anaerobic digestion systems requires significant upfront investment, especially for large scale projects. ii. Technical complexity. Anaerobic digestion systems require proper design, operation and maintenance. iii. Land and space requirements. Anaerobic digestion systems especially large scale projects require significant land and space for installation.

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Table 2.1 Advantages and Disadvantages of WtE Technologies (Cont'd)

MFC	i. MFCs can utilize a wide range of organic waste materials as fuel sources, including wastewater, agricultural waste, and organic by-products. ii. MFCs provide a dual benefit by not only generating electricity but also enabling the treatment and removal of organic waste. iii. MFCs have a smaller carbon footprint relative to traditional fossil fuel-based power generation methods. iv. MFCs can operate under various environmental conditions and can be implemented in diverse settings suchlike wastewater treatment, in remote areas and even in portable devices	i. MFCs have relatively lower power output than conventional energy sources. ii. The microbial processes involved in MFCs are inherently slow, leading to slow reaction rates and reduced power generation efficiency. iii. MFCs require proper maintenance and monitoring to ensure optimal performance. The presence of microbial communities and their interaction can be complex therefore requiring careful management and control. iv. Despite significant advancements, MFC technology is still in its early stages of development. Further research is needed to improve its efficiency, scalability, and cost effectiveness.

(Source: FEAM, 2012; Beyene *et. al*., 2018; Santos *et. al., 2018*; Chakraborty *et. al*., 2013; Kalyani and Pandey, 2014; Moraes, 2016; Sipra *et. al*., 2018)

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2.6 Status of Waste Incineration Facilities Worldwide

Waste incineration with energy recovery is recognized as one of the most advanced WtE technologies employed globally (Dong *et. al.*, 2018). This approach has achieved significant success within the EU, particularly in countries like Germany, France, Italy, the United Kingdom, and Sweden, which have made substantial investments in this technology (Hu and Tao, 2018). A study (Waste to Energy Plants in Europe in 2017) highlights that, in the year 2017 alone, over 96 million tonnes of solid waste were managed by over 492 WtE plants across the EU. Among these, Sweden has emerged as a standout performer in efficiently treating its MSW using waste incineration with energy recovery. The country boasts of approximately 34 waste incineration facilities, producing electricity to supply around 250, 000 households (Waste to Energy Plants in Europe in 2017; Best Recycling Practices around the world). Furthermore, Sweden has significantly reduced its landfill disposal, with merely 0.5 % of generated MSW sent to landfills, and more than 50 % of household waste treated through waste incineration facilities (Waste to Energy Plants in Europe in 2017). Japan holds the highest count of active waste incineration facilities globally, estimated around 1,900, contributing to the management of over 80 % of the nation's MSW (Tan *et. al.*, 2015). These facilities collectively generate a substantial power output of approximately 10,153 GWh (Japan Power Generated by Waste Incineration Plants) – a testament to the country's utilization of waste incineration in waste management.

In the United States, approximately 77 operational waste incineration facilities are distributed across 25 states, responsible for incinerating roughly 7 % of the nation's total MSW (equivalent to approximately 90,000 tonnes per day). These facilities collectively generate a base load electrical capacity of about 2,700 MW, capable of powering over 2 million American households (Executive Summary, 2020). However, unlike the EU and Japan, the widespread adoption of waste incineration for MSW management in the USA has been limited, and this has been attributed to factors such as the availability of ample land for landfilling, and public resistance stemming from historical concerns about air pollution associated with early waste incineration facilities (United States Environmental Protection Agency, 2022).

China has introduced guidelines to reduce landfill use, prompting the adoption of various WtE technologies, including waste incineration, for MSW management (Han *et. al.*, 2016;

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Ji *et. al*., 2016). Notably, studies (China Electricity Council, 2019; National Bureau of Statistics in China, 2020) reveal that in 2019, China combusted approximately 121.7 million tonnes of waste in diverse waste incineration facilities, yielding a remarkable 60.7 billion kWh of electricity. This achievement positions China as a global leader in installed capacity and electricity generation through WtE technology.

The practice of waste incineration is also gaining traction in densely populated developing countries like Brazil, Pakistan, Indonesia, Nigeria, and Bangladesh, which face significant MSW challenges and high energy demands (Lino FAM and Ismail KAR, 2018; Mia *et. al.*, 2018; Starostina *et. al.*, 2018).

2.7 Status of WtE Technology in Ghana

A research study (Ofori-Boateng *et. al.*, 2012) projected that Ghana possesses approximately 12 regulated waste incinerators that lack energy recovery functionality, alongside roughly 232 unregulated waste incineration sites dispersed across the country. This study also detailed the existence of a waste incineration facility planned for commissioning in Kumasi, anticipated to yield between 30 to 52 MWh of electricity from processing 1000 tonnes of MSW. Unfortunately, no subsequent data regarding the present operational status, location, or condition of this aforementioned waste incineration plant was uncovered.

Additionally, there are indications of a WtE plant slated for commissioning in Atwima Nwabiagya district of Ghana's Ashanti region. Once operational, this WtE facility aims to generate approximately 200 kW of solar power, 100 kW of biogas, and an extra 100 kW from the pyrolysis of plastic waste. This WtE plant is highlighted as the pioneer of its kind in Ghana (Hybrid waste-to-energy plant in Ghana).

2.8 Selection of an Optimum WtE Technology

The choice of the most suitable technology for a specific location can be intricate, as numerous factors must be into account. Many researchers have proposed various factors for assessing the optimal WtE technology for a given site. Nevertheless, an investigation (Executive Summary, 2020) emphasized three key aspects (excluding the cost of the technology) that are pivotal in the selection of a WtE technology for a specific area.

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2.8.1 State of Technology

The initial and vital factor to assess is the status of the technology being considered for adoption. This encompasses i. Evaluating the extent to which the technology has been successfully implemented on a commercial level, acknowledging that some technologies might only have undergone pilot or laboratory testing, ii. Reviewing the operational track record of the technology, iii. Ensuring the technology has a low susceptibility to failure modes, and 4. Verifying the overall system's proven reliability.

2.8.2 Technical Performance

The next factor to take into account is the technical effectiveness of the chosen WtE technology. This involves i. Evaluating how well the technology aligns with the complete waste management system at the implementation site, ii. Assessing the technology's capacity to generate marketable final products, and iii. Determining whether any pre-processing of MSW is required at the technology's implementation site.

2.8.3 Technical Resources

The final yet equally important factor to take into consideration is the accessibility of technical resources for the selected technology. This aspect encompasses: i. Established contractor expertise in the technology within the specific location, ii. The proximity of technical assistance for the chosen WtE technology, and iii. The consistent availability of ongoing support.

2.9 Choice of WtE Technology

It is evident from literature that the disposal and management of MSW is really challenging in nations worldwide. However, the use of waste incineration with energy recovery has proven to an attractive WtE technology in the disposal and management of the voluminous amounts of MSW generated worldwide. It is also evident from literature that waste incineration is the WtE technology which is widely employed in developed nations and is gradually gaining recognition in some developing nations as well.

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Thermochemical conversion methods like gasification and pyrolysis have also shown to have great potentials. However, there a few of such facilities operating worldwide. A study (Executive Summary, 2020) indicates there are at least two gasification plants fired with MSW in operation in Japan, and a few other relatively smaller gasification plants, which are in operation in Europe and Asia. Additionally, gasification and pyrolysis reactors fired by MSW are relatively not mature WtE technologies, with most of them being at either pilot stage or under research.

Waste incineration with energy recovery is the only WtE technology which has been proven commercially for over five decades, with over 2000 plants in operation worldwide. It has a mature industry which has been addressing high risks failures and currently with design codes and operational procedures (WtE Guidebook). It is the only WtE technology with plant availability of between 92 to 96 % and many plants with life spans which exceed 20 to 30 years (Executive Summary, 2020). Waste incineration can be used in the management of all composition MSW streams including treated lumber, a limited percentage of tyres and mercury containing devices. There is the availability of a market for the by-products from waste incineration like electricity (waste incineration facilities can generate over 600 kWh of electricity per tonne of waste), steam, hot water, ferrous and non-ferrous metals, and aggregates which can be used as landfill cover. In waste incineration facilities, there may be no need for pre-processing of the MSW apart from the removal of bulky items of waste delivered (which mostly may constitute an insignificant percent of the MSW) (Soares *et. al*., 2017). waste incineration has less environmental impact relative to landfilling (Santos *et. al*., 2019). Waste incineration is a WtE technology which can improve on the management of MSW in Ghana, while contributing to the energy security of the country.

2.10 Current Status of Electricity Generation in Ghana

In Ghana, the primary source of electricity generation is derived from thermal power plants, accounting for approximately 66 % of the total, followed by hydroelectric power plants contributing around 33 %, while solar plants constitute the remaining portion. The thermal power plants in operation within Ghana are powered by sources such as natural gas, diesel, crude oil, or heavy fuel oil. Realizing the cumulative installed capacity of the thermal power plants operating in Ghana is often challenging. This discrepancy can be

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attributed to factors like insufficient fuel supply, variations in hydrological conditions, and deteriorated infrastructure (USAID, 2019). As a result, there is an ongoing need to explore alternative sustainable energy sources that have minimal impact on the environment.

2.11 CO_2 Emissions from the Electricity Power Sector

The electricity power sector involves the generation, transmission, and distribution of the electric power. One of the major concerns from this very important sector of the economy is the huge amounts of greenhouse gas emissions from this sector. According to the US-EPA (USEPA, 2023), CO_2 makes up the greater percentage of emissions from the sector, with smaller amounts from methane, and nitrous oxide. These gases are usually released during the combustion of fossil fuels (suchlike coal, natural gas, oil, and diesel) in the process of electricity generation. The amount of CO_2 released from thermal power plant differ from plant to plant, depending on the type of fuel that is combusted in the combustion chambers of these power plants, since the carbon intensity of fuels differ from one fuel to another.

2.12 Reducing CO_2 Emissions from Electric Power Production

There are various available opportunities, that can be employed to reduce the amount of CO_2 emissions that are associated with electricity power production, transmission, and distribution.

The USEPA identified five reduction opportunities that can be employed to reduce the quantum of CO_2 emissions from the electricity power sector, and these are,

- Enhancing the efficiency of power plants that rely on fossil fuels and exploring fuel substitution. This objective can be achieved through the adoption of advanced technologies, substituting with fuels that have lower carbon content, and transitioning electricity generation from high emission to low emission power plants.
- Opting for renewable energy resources in lieu of fossil fuels for electricity production. It is important to highlight that the USEPA categorizes energy generation from waste as a form of renewable energy.

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- Elevating energy efficiency at the point of consumption by reducing electricity usage and peak demand through improved energy efficiency practices and conservation measures in households, businesses, and industrial settings.
- Generating electricity through nuclear energy as an alternative to the combustion of fossil fuels.
- Capturing and storing carbon dioxide (CO_2) through a process known as carbon capture and sequestration. This process involves capturing CO_2 produced as a result of fossil fuel combustion before it is released into the atmosphere, transporting it, and then injecting it deep underground into specifically chosen and suitable geological formations for secure containment.

2.13 Waste Incineration Technology

Waste incineration facilities with energy recovery are in principle similar to power plants that are fired by fossil fuels. A typical waste incineration facility with energy recovery consists basically of i. The waste storage ii. Boiler or incinerator iii. A steam turbine, and iv. A flue gas treatment system. Figure 2.9 illustrates a complete typical waste incineration facility with energy recovery.

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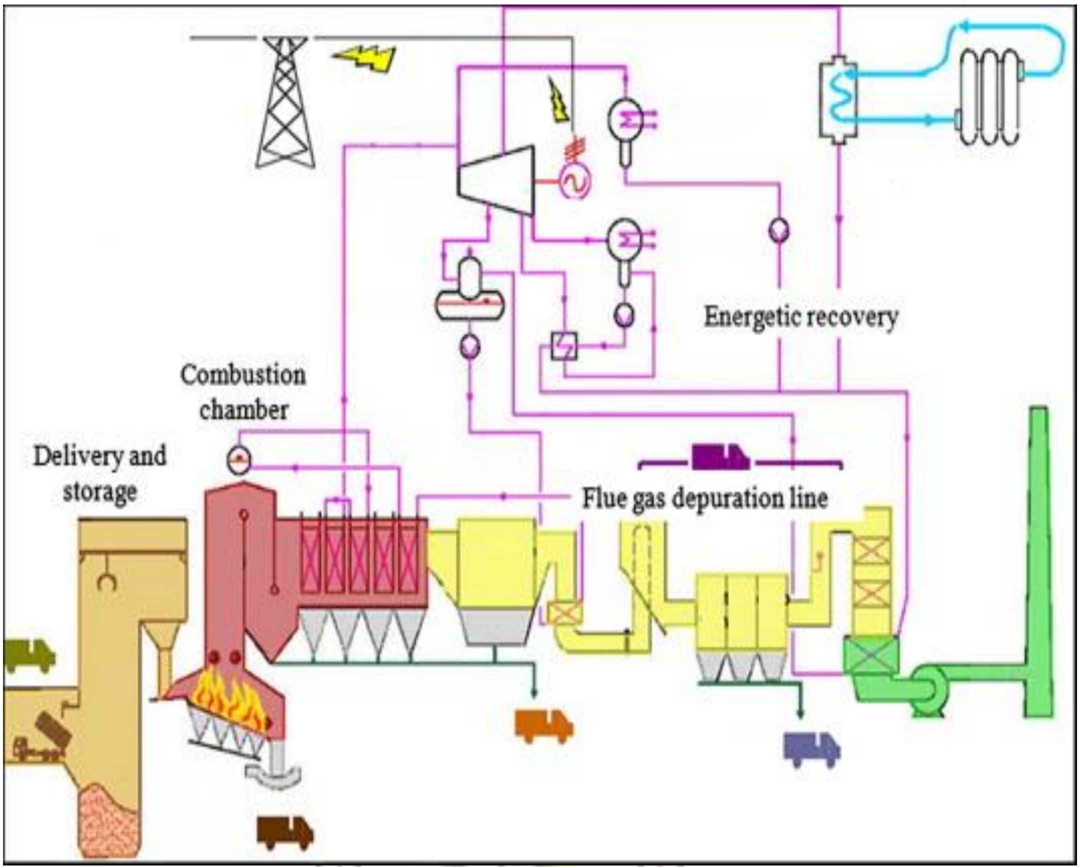

Figure 2.9 A Waste Incineration Plant with Energy Recovery

(Source: Panepinto and Zanetti, 2018)

2.13.1 Waste Storage

In a waste incineration facility, waste is first stored in a controlled manner so as to ensure safe and efficient operation of the facility. The following are some common practices that may be adopted for waste storage in a waste incineration facility.

i. Waste reception and Inspection – before being stored, the waste is received and inspected to look out for bulky items, hazardous materials, or other items that may be non-combustible, which may interfere with the incineration process. Any non-combustible or hazardous waste is separated and disposed of separately.

ii. Waste Sorting and Segregation – after inspection, the waste is sorted and segregated based on its composition and combustibility. This helps to ensure consistent and efficient incineration process and as well as reduces emissions from the process.

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iii. Waste Storage – after sorting and segregation, the waste is stored in appropriate containers, such as sealed drums or bags, or in bulk storage areas. The storage area should be designed to prevent the release of odour or emissions and should be located away from sensitive receptors such as residential areas or sensitive ecosystems.

iv. Waste Inventory and Tracking – the facility should maintain a record of the waste stored, handled, and transported, including information on the composition, quantity, and location of the waste. This helps to ensure that the waste is managed safely and efficiently and can assist with regulatory compliance.

2.13.2 Boiler or Incinerator

The boiler or incinerator is a critical component of a waste incineration facility, as it is responsible for the combustion of the waste and the generation of steam and/or electricity. the following are some key features and considerations for the boiler or incinerator in a waste incineration facility:

i. Combustion chamber: the combustion chamber is where the waste is burned and is designed to achieve complete combustion and minimize emissions. The chamber may be designed for either vertical or horizontal combustion, depending on the type of waste and other facility requirements.

ii. Grate system: the grate system is used to transport the waste through the combustion chamber and is designed to ensure uniform and efficient combustion. There are several types of grate systems, including reciprocating, vibrating, and fluidized bed.

iii. Heat Recovery system: the heat recovery system is used to capture the heat generated by the combustion process and convert it into steam or hot water for use in power generation or heating applications. The heat recovery system may include a boiler, heat exchangers, and other components.

iv. Monitoring and control: the boiler or incinerator should be equipped with monitoring and control systems to ensure safe and efficient operation. These systems may include sensors for temperature, pressure, and

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emissions, as well as automated controls for adjusting combustion and air flow rates.

2.13.3 Steam Turbines

Steam turbines are commonly used in waste incineration facilities with energy recovery to convert the heat generated by the combustion of waste into electricity. The following are some key features and considerations for steam turbines used for electricity generation in a waste incineration facility.

i. Turbine Type: the type of steam turbine used in a waste incineration facility depends on several factors, including the amount and temperature of the steam generated, the electrical output required, and the facility's specific needs. The most common types of steam turbines used in waste incineration facilities are condensing and back-pressure turbines.
ii. Steam Supply: the steam supply to the turbine is critical to ensure safe and efficient operation. The steam must be at the proper pressure, temperature, and quality to meet the requirement of the turbine and prevent damage or failure. The steam supply may be generated by a heat recovery boiler, which converts the waste heat from the incinerator into steam.
iii. Control Systems: The steam turbine and generator must be equipped with control systems to ensure safe and efficient operation. These systems may include sensors for monitoring steam flow, pressure, and temperature, as well as automated controls for adjusting steam flow rates and turbine speed.
iv. Maintenance and Upkeep: steam turbines require regular maintenance and upkeep to ensure safe and efficient operation over their lifespan. Maintenance may include regular inspections, cleaning, and repair or replacement of components as needed.
v. Generator: the generator is responsible for converting the rotational energy of the steam turbine into electrical energy. The size and capacity of the generator depend on the electrical output required by the facility.

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2.13.4 Flue Gas Treatment System

A flue gas treatment system is an essential component of a waste incineration facility that is used to remove pollutants and other harmful substances from the flue gases generated during the combustion process. The following are some key features and considerations for a flue gas treatment system in a waste incineration facility:

i. Flue Gas Cleaning: flue gas cleaning is the process of removing particulate matter, heavy metals, and other pollutants from the flue gases generated by the incinerator. The cleaning process typically involves a combination of physical and chemical methods, including electrostatic precipitators or bag filters for particulate matter removal, and scrubbers or activated carbon injection for removal of acid gases.

ii. Flue Gas Monitoring: the flue gases must be continuously monitored to ensure that they meet regulatory requirements for emissions. The monitoring system should include sensors for temperature, flow rate, and the concentration of pollutants, such as Nitrogen Oxide (NO_X), Sulphur Dioxide (SO_2), and Carbon Monoxide (CO).

iii. Scrubbing System: A scrubbing system is a key component of the flue gas treatment system that is used to remove acid gases, such as sulphur SO_2, HCl, etc., from the flue gases. The scrubbing system typically includes a wet scrubber that uses a chemical solution to absorb the acid gases.

iv. Activated Carbon Injection: activated carbon injection is used to remove mercury and other heavy metals from the flue gases. Activated carbon is injected into the flue gases, and the metals are adsorbed onto the carbon particles, which are then removed from the flue gases.

v. Maintenance and upkeep: the flue gas treatment system requires regular maintenance and upkeep to ensure that it is operating effectively and efficiently. Maintenance may include regular inspections, cleaning, and repair or replacement of components as needed.

2.14 Emission Control Strategies in Waste Incineration Facilities

Combustion processes comes with the release of huge volume of exhaust gases, and waste incineration plants are no exception. The pollution from the emission of flue gases from

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waste incinerators has been a major setback of the waste incineration technology, therefore, it is very important to employ mechanisms that can mitigate the effects of these emissions from waste incinerators.

Emission control strategies employed in waste incineration plants are generally grouped into two, thus operational, and Air Pollution Controls (APCs) systems. Operational controls (also referred to as combustion controls) are usually employed in modern waste incineration plants to increase the plants performance in respect to its efficiency and at the end reduce the formation of certain emissions that would have been generated by the plant. APCs (also referred to as post combustion controls) on the other hand are employed in modern waste incineration plant to treat the emissions before they are released into the atmosphere. To meet stringent emission limits set out by environmental protection agencies in developed nations, both control strategies are an integral part of modern waste incineration facilities.

2.14.1 Operational Controls

Operational controls (also referred to as combustion controls) are employed on modern waste incinerators to limit the conventional and trace contaminants that would be produced during the combustion process. These controls are to compensate for the natural variability in the quality of MSW as fuel and controls factors that govern the rate of chemical reactions. There are basically three (3) conditions that must be fulfilled to aid in the reduction of organic emissions, and these are;

i. Ensuring complete mixing of the fuel (which in this case is MSW) and air.

ii. Maintaining sufficiently high temperatures in the combustion chamber in the presence of sufficient oxygen and

iii. Prevention of the formation of low temperature pathways (what is referred to as quench zones) that may allow partially reacted solids or gases to exit from the combustion chamber.

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2.14.2 Air Pollution Controls

Air Pollution Controls (APCs) are designed to clean by products from combustion of the MSW emanating from the combustion chambers of the incinerators and boilers to acceptable levels set out by environmental protection controlling agencies. The various elements comprising the APCs systems are integrated to create a cohesive and efficient overall system designed to treat pollutants within the flue gases. Flue gases or the by-products from the combustion of MSW consists of

i. Gaseous products of combustion mainly carbon dioxide hydrogen chloride, oxides of nitrogen, sulphur dioxide, and others depending on the composition of the MSW.
ii. Vapour forms of organics and as well as that of metals, and
iii. Solid Particulate Matter (PM), also referred to as fly ashes.

2.15 Acidic Gas Cleaning

Cleaning acidic gases from flue gases emanating from the combustion of MSW in waste incineration plants can be done employing three main methods. Thus, the dry, semi-dry and wet methods.

The dry method of acidic gas cleaning in waste incineration are carried out by using mostly calcium hydroxide ($Ca(OH)_2$), sodium bicarbonate ($NaHCO_3$), or calcium carbonate ($CaCO_3$). The injection of these compounds is done by injecting them directly into the furnace, ducts, or both (hybrid), or by use of a fluidised bed reactor (Pajak *et. al*., 2015).

Advantages of the dry method includes simplicity in the technology, there is no need for conditioning of flue gas before cleaning, no production of wastewater after the process, and lower operating costs. Disadvantages includes, lower efficiency (30 to 40 %), higher costs of disposal of the residuals from the process (Pajak *et. al*., 2015).

The semi-dry method uses an agent which is in liquid form (thus an aqueous solution of activated carbon and calcium hydroxide). The agent used in this method is removed from the reactor after evaporation of water and reaction with the acidic gases in dry form. In the semi-dry method, there is conditioning of the flue gases to a lower temperature, which is usually kept above a temperature of 120 ℃, so as to avoid the formation of hygroscopic

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calcium chloride (Mokrosz, 2010), which can be formed with the flue gases rich in HCl. This method of acidic gases cleaning is mostly employed in conjunction with fabric filter type of particulate matter separation device where most of the reactions occurs (Piecuch, 1998). Advantages of this technology includes no production of wastewater after the process, simplicity in the technology, and production of a dry residual. Disadvantages includes, the absorbent used in this process is more expensive relative to that used in the wet method, higher demand for compressed air, higher cost of investment relative to the dry method (Pajak *et. al*., 2015).

In the wet method of cleaning acid gases from flue gas stream, the agent added is in the liquid form as well as the product is also in liquid form. It is estimated that 87 % of traditional thermal power plants worldwide employs this type of acid gas cleaning method (Benko and Mizsey, 2007).

A typical design of a limestone wet method of FGD technology has two basic stages. In the first stage, only water (acidic condition) is added. This stage is only effective in the removal of HF, HCl and SO_3. The removal of SO_2 in the first stage is low due to the presence of HCl which affects its absorption. Therefore, a second stage is incorporated where a liquid with higher pH (neutral or alkaline condition) is added to remove the SO_2. The second stage is reported to be capable of removing other acidic compounds that are present in the flue gas stream (Neuwahl *et. al*., 2019; Johnke, 2001; Hellman, 2015; Goldschmidt and Carlstrom, 2011; Matthews, 1998). Advantages of this technology includes higher efficiencies (above 90 %), low consumption of absorbent during the process, lower sensitivity to fluctuations in the flow, and the residual from the process is in the form of gypsum which can be used in other chemical processes. Disadvantages of this technology includes, requires a larger area for installation, and the production of wastewater after the process which must be treated before reuse or disposal into the environment (Pajak *et. al*., 2015). Figure 2.10 depicts the various methods in a non-regenerative FGD technologies that are used in acid gas cleaning.

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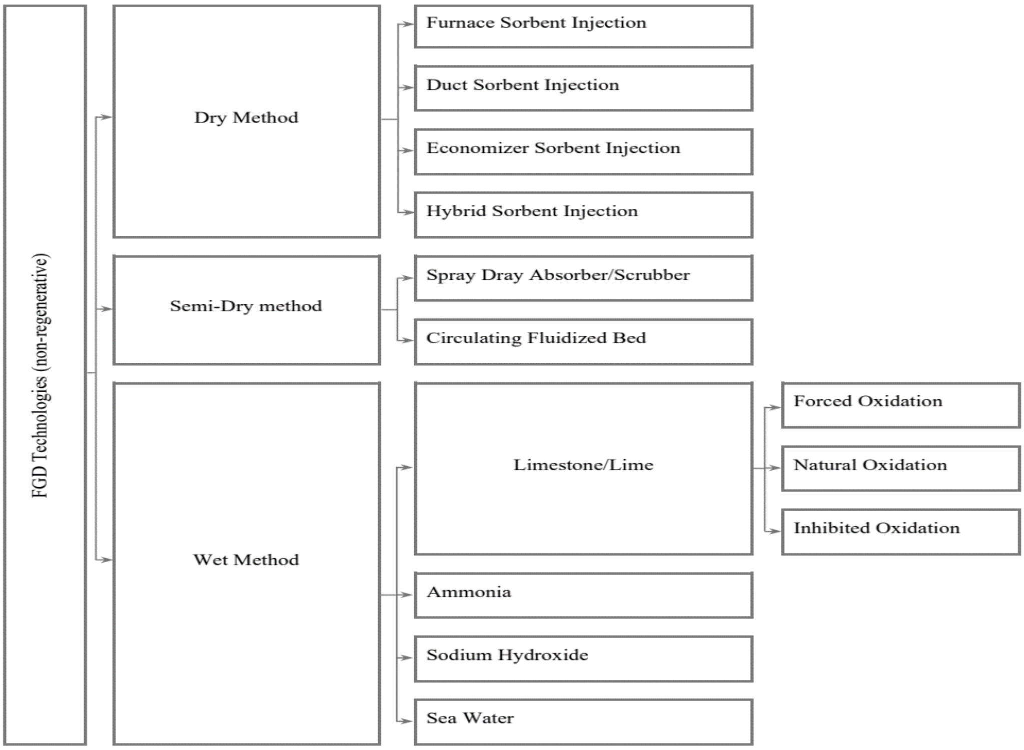

Figure 2.10 Non-regenerative Flue Gas Desulphurization Technologies (Source: Jurczyk *et. al*., 2016)

Typical chemical reactions in wet scrubbing processes are as;

i. HCl absorption: $HCl + NaOH \rightarrow NaCl + H_2O$
ii. HF absorption: $HF + Ca(OH)_2 \rightarrow CaF_2 + 2H_2O$
iii. SO_2 absorption: $SO_2 + H_2O \rightarrow H_2SO_3$
iv. H_2SO_3 Oxidation: $2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$
v. H_2SO_4 reaction with lime or limestone:

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$$

The resulting neutral salts formed (such as sodium chloride and calcium fluoride) can be disposed of safely or used in other industrial processes.

2.16 Particulate Matter and its Separation

Particulate Matter (PM) is defined as a complex combination of either solid or liquid particulates produced from combustion processes that are suspended in the air. In waste incineration plants this solid particulate matter must be removed from the flue gas stream

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before it exits the stack into the environment. There are basically three types of PM separation devices that are employed in the separation of PM from flue gases emanating from waste incineration plants. These are the cyclone, fabric filter, and electrostatic precipitator.

2.16.1 Cyclone

The cyclone (also referred to as cyclone separators, cyclone collectors, inertial separators, or centrifugal separators), is a type of PM separation device which is operated by using inertial and centrifugal forces induced by cyclone to create a double vortex on the gas stream to remove heavy particles in the gas. Cyclones may be used in single or in multiples.

Cyclones are used to control PM which are primarily greater than 10 µm in aerodynamic diameter. There are, however, high efficiency cyclones design which can effectively remove PM between 2.5 µm to 10 µm in aerodynamic diameter. Although, the collection efficiency of cyclones is affected directly by the cyclone's design and particulate size, but generally, its collection efficiency increases with increase in the following;

i. Inlet duct velocity
ii. Cyclone's body length
iii. Particle size and/or its density
iv. Number of gas revolutions in the cyclone
v. The ratio of cyclone body diameter to gas exit diameter
vi. Dust loading and
vii. The smoothness of the inner walls of the cyclone employed.

An increase in the following factors, however, will cause a decrease in the cyclone's removal efficiency, gas viscosity, body diameter, gas exit diameter, gas inlet duct area, and gas density. There are three designs of the cyclone PM removal device, namely, conventional, high-efficiency, and high-throughput. Figure 2.11 shows a diagram of a cyclone PM removal device.

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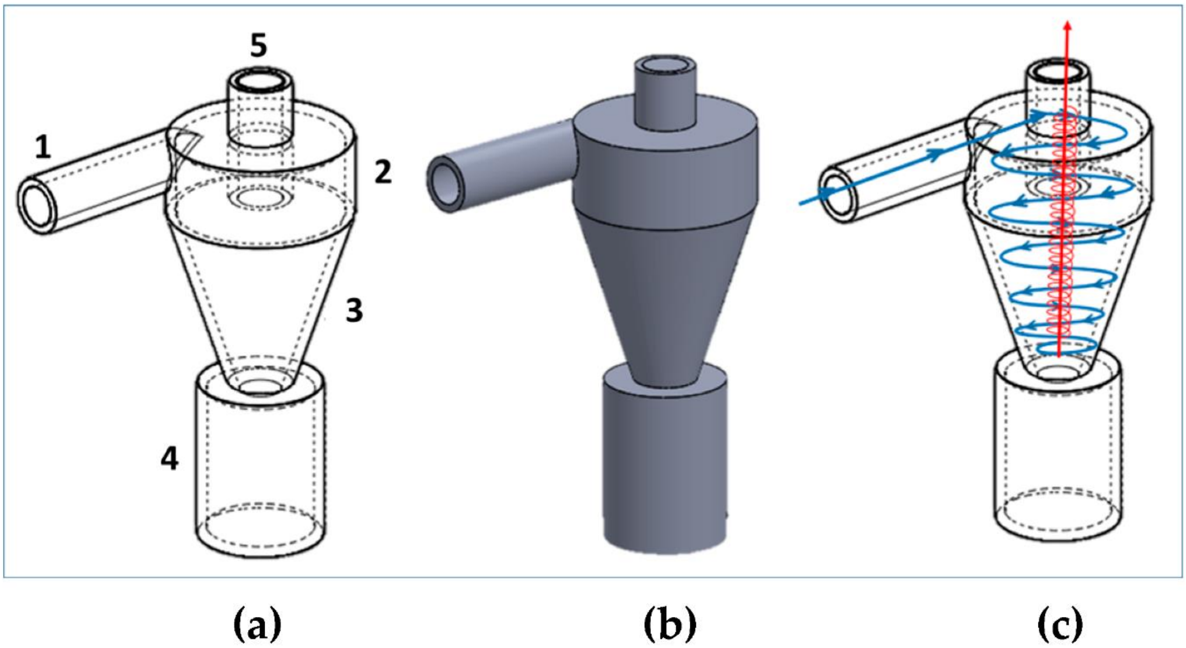

Figure 2.11 Diagrams of a Cyclone PM Removal Device

(Source: Rivera-Garcia *et. al*., 2023)

The separation (or control) efficiency for a conventional single cyclone is estimated to be between 70 to 90 % for PM_{20}, 30 to 90 % for PM_{10} and 0 to 40 % for $PM_{2.5}$. High efficiency single cyclones are designed purposely to achieve higher control efficiencies for smaller particles than that in the single conventional cyclones. Cooper (1994) estimated that high efficiency single cyclone can achieved efficiencies up to 90 % in control of PM_5 with efficiencies higher than 90 % when removing particles greater than 5µm. The separation efficiency for high throughput is estimated to between 80 to 99 percent for PM_{20}, 10 to 40 % for PM_{10}, 0 to 10 % for $PM_{2.5}$. Vatavuk (1990) reported that high throughput PM cyclones is only guaranteed for PM sizes of 20µm. EPA (1998) reported removal efficiencies of between 80 to 95 % for 5µm can be achieved with the use of multicyclone.

2.16.2 Fabric Filter

A fabric filter, commonly known as a baghouse, functions as a device for separating particulate matter (PM) by employing fabric filtration to extract particles from a polluted gas stream and deposit them onto the fabric material. The process of filtration primarily

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occurs when the gas stream containing particles is directed through the fabric material, typically a porous and solid medium, which captures the particles within the gas. The filter's effectiveness in removing fine particles is attributed to the build-up of dust rather than solely relying on the properties of the fabric itself. Figure 2.12 shows a diagram of a typical fabric filter PM removal device.

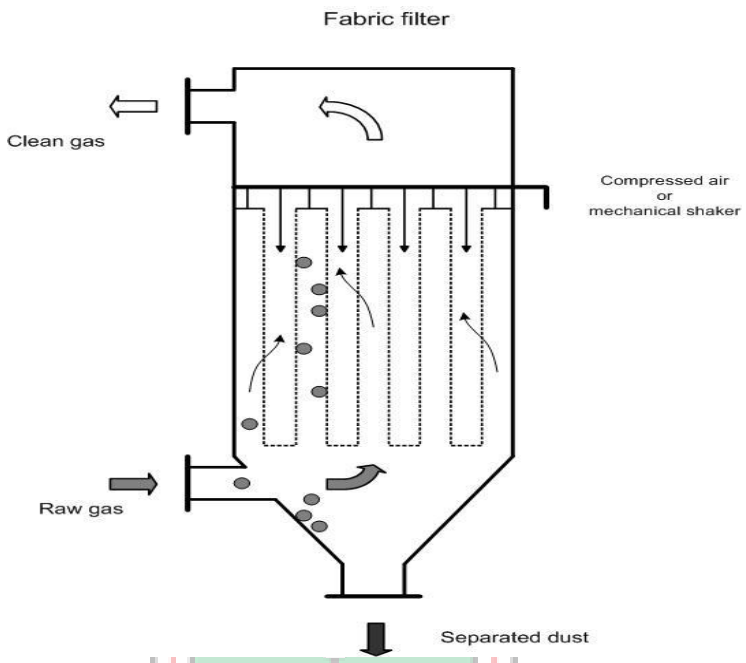

Figure 2.12 A Fabric Filter PM Removal Device

(Source: Emis, 2020)

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According to the Environmental Protection Agency (EPA) in 1998, fabric filters are reported to achieve collection efficiencies exceeding 99 %. Essentially, there are three main types of fabric filters in use: the shaker baghouse, reverse air baghouse, and pulse jet baghouse. In sizing and operating a baghouse, two fundamental parameters are typically considered: the air-to-cloth (A/C) ratio and the pressure drop across the filters. Other factors that significantly influence the performance of baghouses include the particle size distribution, the composition of the fly ash, the temperature, moisture levels, and the dew point of the flue gas (Miller, 2010).

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2.16.3 Electrostatic Precipitator

An Electrostatic Precipitator (ESP) is a PM separation device which removes particles from a gas stream by using electrical energy to charge particles (either negatively or positively). The charge particles are then removed by the collector material either as dry material (in dry ESPs) or washed from the surface with the use of water (in wet ESPs). ESPs are reported to be capable of achieving collection efficiencies above 99 % (Zukeran *et. al*., 1999). Figure 2.13 is a diagram which illustrates the operation of an ESP particulate matter separation device.

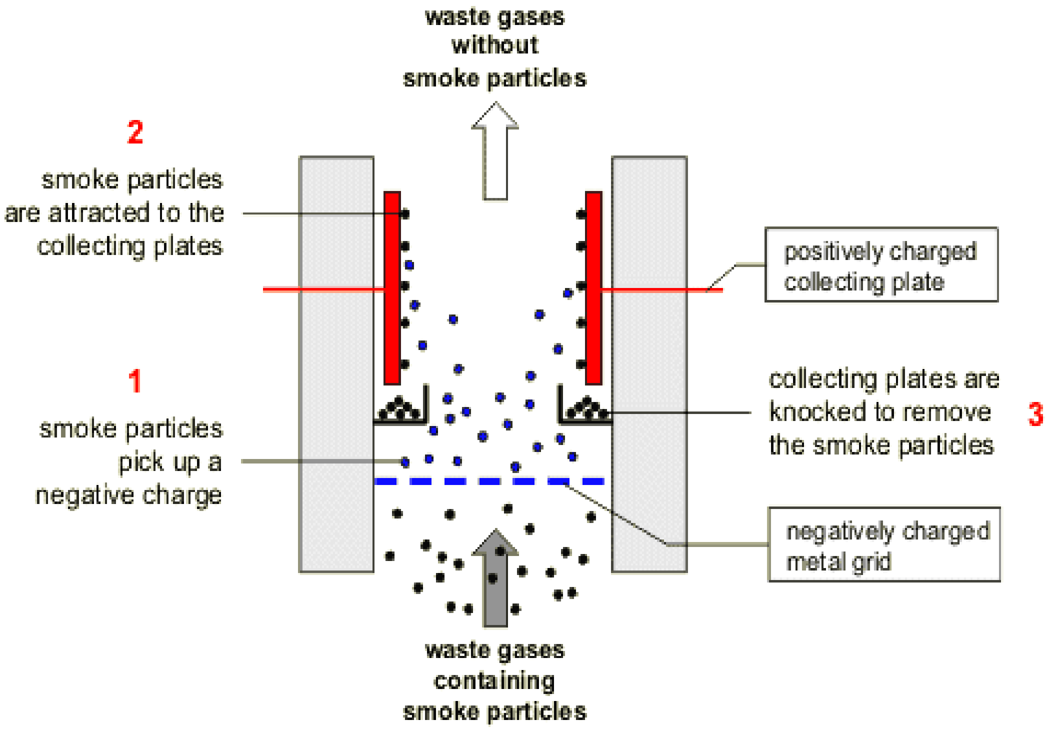

Figure 2.13 A Diagram of an ESP PM Removal Device

(Source: Enviraj, 2018)

There are four main components that are used in ESPs to function. These are the gas distribution plates, discharge electrodes, collection surface (which can be a plate or a pipe), and the rappers.

The gas distribution plates comprise multiple perforated plates and serve to ensure proper flow distribution of the flue gas stream upon entry into the device. The discharge electrodes are typically divided into two or more fields arranged in series, powered by a

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Transformer Rectifier (T-R) set power supply. The collection plate or pipes provide the surfaces where charged particulate matter is attracted. The rappers play the role of dislodging the collected particulate matter from the collection surfaces.

ESPs are generally categorized as either dry or wet. The primary distinction lies in how the collector plates or pipes are cleaned. In dry ESPs, cleaning is achieved through mechanical impulses or vibrations that dislodge the loosely collected particulate matter (also known as rapping). Conversely, in wet ESPs, cleaning is accomplished by rinsing the collector plates or pipes with water.

2.17 Dioxins/Furans, formation, and Control

Dioxins are unwanted by-products from combustion which have generated a lot of controversies because, it is among the most toxic environmental compounds. A study (USEPA 2023) indicates that, dioxins are serious carcinogen substances that can destroy the human immune system and interferes with hormones and regulation.

These are compounds that are unintentionally generated in combustion processes (including waste incinerators) in two ways (Chang *et al*., 2011; Choi and Lee 2007; Liu *et al*., 2013).

i. Homogeneous reactions take place within the temperature range of 500 °C to 800 °C. This is as a result of the rearrangement reaction of chlorinated precursors like chlorobenzenes (CBs) and chlorophenols (CPs) present in the gas phase. The resulting CDD/Fs formed during this process are known as homogeneous PCDD/Fs or high temperature PCDD/Fs.

ii. The second type involves heterogeneous reactions occurring in the post combustion zone within the temperature range of 200 °C to 400 °C. This phenomenon primarily results from the surface catalytic effect of fly ashes (or soot), commonly known as the De novo process (Stanmore 2004; Huang and Buekens, 1995). PCDD/Fs generated through this mechanism are termed heterogeneous or low temperature PCDD/Fs and can originate from chlorophenols and chlorobenzenes (Addink and Olie, 1995; Vermeulens *et. al*., 2014), as well as from the carbon present in the fly ash.

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The control of dioxins/furans in flue gas streams is by use of Activated Carbon Injection (ACI). In an ACI, activated carbon is injected into the flue gas of the incinerator, where it adsorbs the dioxins and furans. The carbon injected is then removed from the system, however, it should be disposed of as hazardous waste.

Another method that can be used in removing dioxins and furans from flue gases emanating from waste incineration facilities is the use of Selective Catalytic Reduction (SCR) technology. SCR technology involves the injection of urea or ammonia into the flue gas stream, which reacts with the nitrogen oxide emissions from the combustion of the solid waste to form a harmless nitrogen and water. This process can significantly reduce the levels of dioxins and furans produced in the flue gas stream.

2.18 Wastewater Treatment and Membrane Distillation

As mentioned earlier in section 2.15, a major drawback of the wet method of cleaning acidic gases from flue gases emanating from waste incineration plants is the production of wastewater. This wastewater must be treated prior to reuse or if it is to be disposed into the environment. There are several methods that can be employed in the treatment of wastewater.

Wastewater treatment involves various methods and processes to remove contaminants and pollutants from the wastewater before it is released back into the environment or reused. The treatment of wastewater involves several methods, and these are, preliminary treatment, primary treatment, secondary treatment, tertiary treatment, disinfection, sludge treatment, nutrient removal, and advanced treatment technologies.

i. Preliminary treatment: this is the initial stage of wastewater treatment and involves physical processes such as screening and grit removal. Larger debris, such as sticks, rocks, and rags are removed through screening, while grit chambers remove heavy inorganic particles like sand and gravel.
ii. Primary treatment: in this step, large, suspended solids and organic matter are removed through physical processes like sedimentation and flotation. Wastewater is held in large tanks or clarifiers, allowing solids to settle to the

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bottom (primary sludge) and oils and grease to float to the top (scum). The settled wastewater, known as effluent, undergoes further treatment.

iii. Secondary treatment: this stage involves biological processes to break down dissolved and suspended organic matter. The most common secondary treatment method is activated sludge, where air and microbial organisms are introduced into the wastewater to facilitate the decomposition of organic pollutants. Other methods include trickling filters and rotating biological contactors.

iv. Tertiary treatment: also known as advanced or final treatment, tertiary treatment aims to further remove remaining contaminants, including nutrients, pathogens, and trace pollutants. Methods employed in tertiary treatment include filtration (sand or membrane), disinfection (chlorination, ultraviolet (UV) light, ozone), and chemical processes (such as coagulation, flocculation, and advanced oxidation).

v. Disinfection: as part of the treatment process, disinfection is applied to kill or inactivate disease-causing microorganisms (pathogens) present in the wastewater. Common disinfection methods include chlorination, UV disinfection, ozone treatment, and chemical disinfectants like chlorine dioxide.

vi. Sludge treatment: the sludge generated during primary and secondary treatment is further treated to reduce its volume and make it more suitable for disposal or beneficial use. Sludge treatment processes include thickening (to reduce water content), digestion (anaerobic or aerobic to break down organic matter), dewatering (to further reduce moisture content), and drying or incineration.

vii. Nutrient removal: some wastewater treatment plants employ specific processes to remove excess nutrients like nitrogen and phosphorus, which can cause environmental issues such as eutrophication in receiving water bodies. Methods used for nutrient removal include Biological Nutrient Removal (BNR), chemical precipitation, and Enhanced Biological Phosphorus Removal (EBPR).

viii. Advanced treatment technologies: in certain cases, advanced treatment technologies may be employed to address specific contaminants or meet stringent effluent quality requirements. These technologies include membrane filtration (reverse osmosis, microfiltration, nanofiltration…), activated carbon

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adsorption, ion exchange, and Advanced Oxidation Processes (AOPs) like ozonation or UV.

It is imperative to note that the specific methods employed in wastewater treatment can vary depending on factors such as the composition and characteristics of the wastewater, local regulations, treatment plant size, and the desired effluent quality. Treatment processes are often combined and customized to meet the specific needs of a particular wastewater treatment facility.

2.18.1 Membrane Distillation: Introduction and Brief History to the Technology

Bodell (1963), introduced a system which was based on an air-filled porous hydrophobic membrane and was to convert non-portable liquids into a drinkable one. His research, however, did not publish the structure, and membrane geometry and the results too were not quantified. Four years later, Weyl (1967) investigated the polytetrafluoroethylene (PTFE) hydrophobic membrane (with thickness of 3.2 mm, pores sizes of 9 mm and porosity of approximately 42 %) which was aim at improving the efficiency of water desalination. Findley (1967), in the same year published the fundamental principles as well the outcomes of the direct contact membrane distillation. The interest in the use of membrane distillation technology received massive boost in the mid-1980s which was attributed to the introduction of a highly porous hydrophobic material.

MD processes can be divided into four basic configurations, and this is based on the techniques used to create vapour pressure gradient across the membrane and collect the transported vapour from the permeate side. The separation performance and operation cost are significantly influenced by the MD configuration. Numerous researchers have suggested some new configurations with increased energy efficiency, better permeation flux, or smaller footprints.

There has been quite a plethora of reviews (Gryta *et. al*., 2006; Lawson & Lloyd, 1997; Alklaibi & Lior, 2005; Curcio & Drioli, 2005; Drioli *et. al*., 2015; Alkhudhiri *et. al*., 2012; Khayet, 2013; Khayet, 2011; Wang & Chung, 2015; Thomas *et. al*., 2017; Jiao *et. al*., 2004) which have presented the details on Membrane Distillation (MD), and this encompasses its development, membrane properties, as well as its potential application. These reviews thus confirm that MD technology has been researched extensively at

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academic levels, where publications are mostly experimentally focused on the development of the membrane materials and parametric investigations.

2.18.2 Working Principle

Membrane distillation is a non-isothermal membrane separation process which presents a two-fold barrier; (i) membrane hydrophobicity that provides high recovery ratios and a high-quality permeate production and (ii) the separation owing to differentiation in the volatility of the various contaminants.

"Membrane distillation" is a term that was originally coined from the conventional distillation process and modified with membrane separation. The main driving force in membrane distillation is usually the temperature difference across the membrane, which creates a vapour pressure difference between the feed and the permeate side of the membrane (El-Bourawi *et. al*., 2006). There are three stages of water transportation in MD technology; (i) the formation of vapourised gas at the interface of the hot feed solution and the membrane surface, (ii) the transportation of the generated water vapour through the hydrophobic membrane, and (iii) the condensation of the water vapour at the interface of the membrane cold side and permeate solution (Jiao *et. al*., 2004).

The phase separation involved in MD process is attributed to the vapour-liquid equilibrium, where usually the condensation/evaporation induces the phase change process (Alkhudhiri *et. al*., 2012). During this process of separation, the latent heat which is associated with the permeate vapour dissipate on the other side of the membrane to the cold stream.

The Knudsen diffusion, molecular diffusion, and the Poiseuille flow (i.e., viscous flow) are three principal mechanisms that governs the mass transfer phenomenon in MD processes. Accordingly, there are specific resistances that are associated with the momentum transfer to the membrane (i.e., viscous resistance), the collision of molecules (i.e., molecular resistance) and finally one with the membrane itself (i.e., Knudsen resistance). However, the mass transfer is usually affected by the thermal boundary layer (Curcio & Drioli, 2005; Alkhudhiri *et. al*., 2012). Figure 2.14 presents the mass transfer resistances in an MD process.

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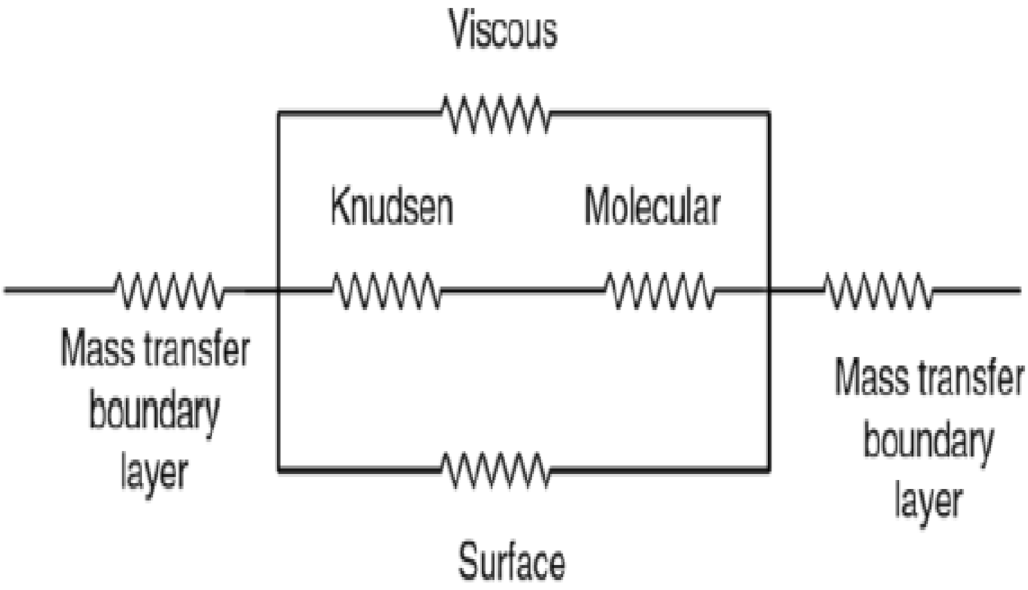

Figure 2.14 The Mass Transfer Resistances in an MD Process

(Source: Alkhudhiri *et. al*., 2012)

Also, in MD separation processes, the heat transfer through the membrane usually occurs through two parallel mechanisms, thus conduction and latent heat transfer (Alkhudhiri *et. al*., 2012). Consequently, different heat resistances are experienced during the process of heat flow, this phenomenon is illustrated in Figure 2.15.

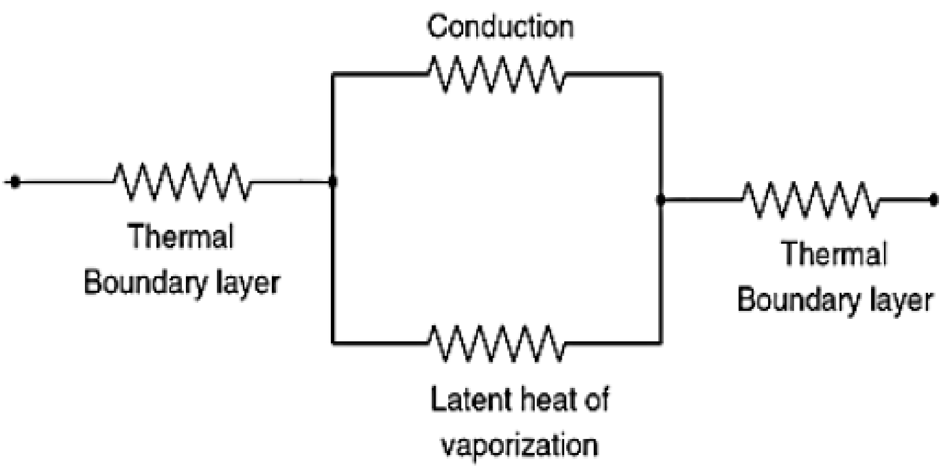

Figure 2.15 The Heat Resistances in MD Process

(Source: Alkhudhiri *et. al*., 2012)

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2.18.3 Basic MD Module Configurations

According to the several ways of producing vapour pressure gradient across the membrane, MD technology can be classified into the following four elementary configurations, and this is illustrated in Figure 2.16 (a) –(d).

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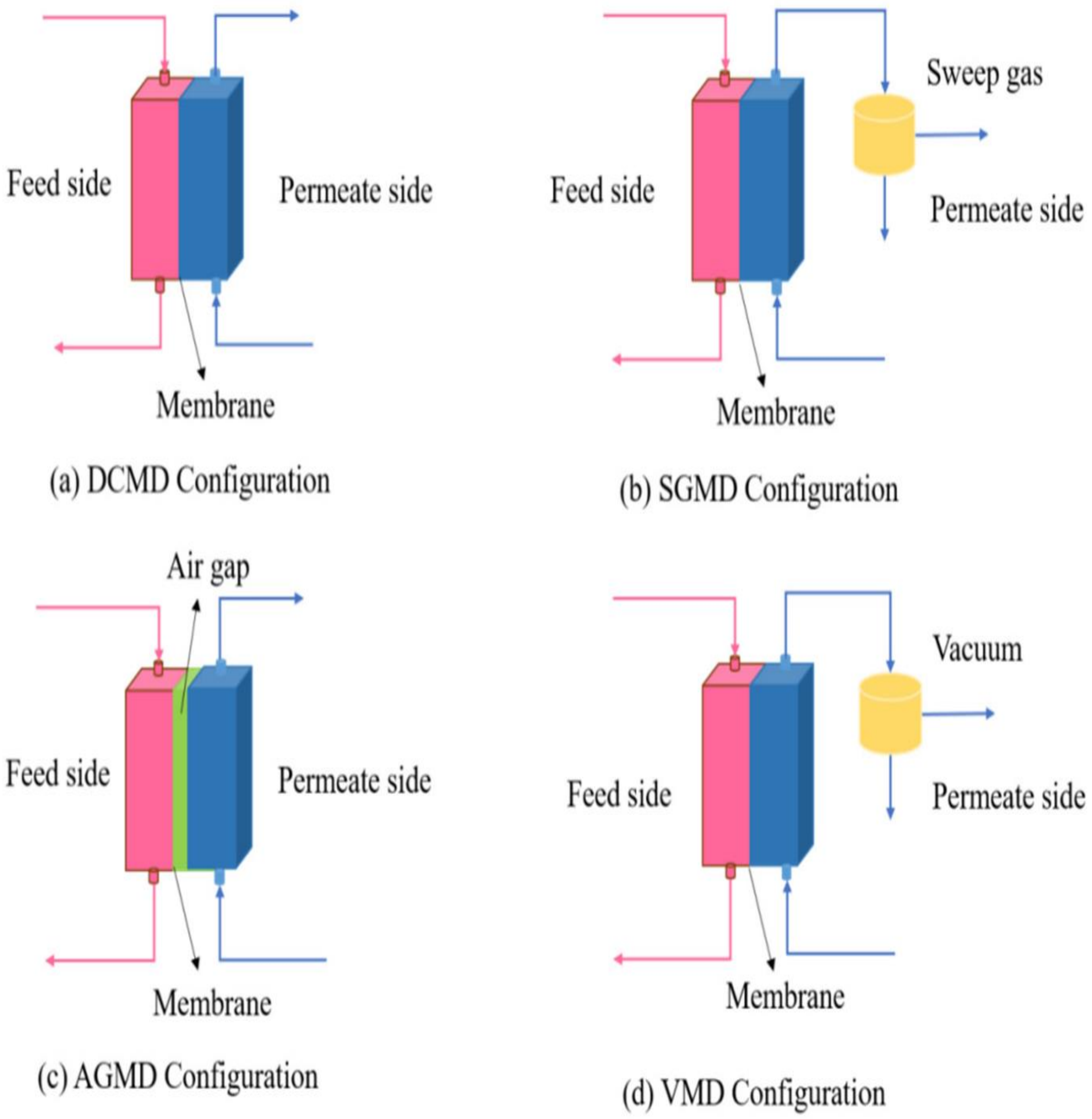

Figure 2.16 The Basic MD Configurations (a) Direct Contact MD (DCMD); (b) Sweeping Gas MD (SGMD). (c) Air Gap MD (AGMD); and (d) Vacuum MD (VMD).

(Source: Yan *et. al*., 2021)

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Direct Contact Membrane Distillation (DCMD)

The hot membrane side surface is in direct contact with the hot solution (feed) in this configuration. Evaporation in DCMD, therefore, occurs at the feed-membrane surface. The vapour is then forced to the permeate side of the membrane by the difference in pressure difference, where it finally condenses inside the membrane module. The hydrophobic property prevents the feed from penetrating the membrane (only the gas phase exists inside the membrane pores). DCMD is the simplest MD configuration and is frequently used in the food industry for desalination procedures and the concentration of aqueous solutions (Alves & Coelhoso, 2006; Gunko *et. al*., 2006; Godino *et. al*., 1997; Hsu *et. al*., 2002; Calabro *et. al*., 1994). It is also used in the formation of acids (Alves & Coelhoso, 2006; Tomaszewska *et. al*., 1995).

Air Gap Membrane Distillation (AGMD)

The movement of vapour molecules across the membrane and the air gap is explained by the molecular diffusion theory. At the air gap side of the membrane, it is assumed that a gas film that is stagnant (air) is present.

In AGMD, a cold condensing plate that collects vapour that travels across the air gap is located between the membrane and the air gap. Experimental testing has been done on air gap systems. Due to its advantageous heat transfer properties, AGMD shows promise as a desalination technology with high energy efficiency. An embedded condenser surface then enables fluid to be condensed at the local saturation temperature rather than being condensed and mixed at the average saturation temperature as in the case of a VMD system. Furthermore, the insulation properties of the air gap then prevent direct thermal loss between hot and cold sides. Optimizing and improving the design of AGMD could make it competitive with more established thermal desalination systems (Summers & Lienhard, 2013).

Vacuum Membrane Distillation (VMD)

In a vacuum MD, a vacuum is usually applied on the permeate side of the membrane module. The applied vacuum, however, must be lower than the saturation pressure of volatile molecules in the feed solution which in turn provides the driving force.

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Condensation may or may not take place outside of the membrane module (Al-Asheh *et. al*., 2006; Li & Sirkar, 2005; Liu *et. al.*, 1998).

Sweeping Gas Membrane Distillation (SGMD)

In the SGMD configuration, a stripping gas is used as a carrier for the vapour transferred from a warm aqueous feed through a porous hydrophobic membrane. Due to the nature of the membrane, liquid cannot enter the pores; because of this, a liquid/vapour interface forms at each pore entrance. The flammable molecules, therefore, evaporate through the membrane pores, and the permeate is swept away from the module by a cold, inert gas flowing along the opposite side of the membrane. Vapour condenses in the SGMD with the use of an external condenser. The driving force for mass transfer in SGMD is generated due to the difference in the partial pressure of volatile substances created on both sides of the membrane. In MD systems, since heat is transferred from the feed side through the membrane, there is a significant rise in both the module's temperature and the sweep gas temperature. However, SGMD combines a reduced mass transfer resistance with a lower conductive heat loss through the membrane. Therefore, there is a higher permeate flux provided by the resulting high mass transfer coefficients than that in DCMD (using the same membrane).

Additionally, there are some modified MD module configurations. These includes the Thermostatic Sweeping Gas Membrane Distillation (TSGMD), Material Gas Membrane Distillation (MGMD), and the Osmotic Membrane Distillation (OMD). These modifications are made to enhance the performance of the basic configurations. Table 2.2 presents the four primary MD configurations, its application areas, advantages, and disadvantages.

2.18.4 Application of Membrane Distillation

Membrane distillation has various applications across different industries. Some common applications of membrane distillation include;

i. Desalination: membrane distillation can be used for desalination processes to produce fresh water from saline or brackish water sources. It is particularly, useful in treating highly saline water or wastewater

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that is usually challenging to treat using conventional desalination techniques.

ii. Concentration of fruit Juices: Membrane distillation can be applied to concentrate fruit juices by removing water while retaining the flavour compounds, vitamins, and other desirable components. It offers a gentle and efficient method for juice concentration without significant heat degradation.

iii. Industrial wastewater Treatment: Membrane distillation is effective in treating industrial wastewater and recovering valuable components or removing contaminants. It can help separate and concentrate specific compounds or purify water streams for reuse.

iv. Removal of Volatile Organic Compounds (VOCs): Membrane distillation can be used to remove volatile organic compounds from water or air streams. It provides an effective separation technique for VOCs removal, making it suitable for air purification systems or water treatment processes.

v. Production of Pure chemicals: Membrane distillation can be employed to concentrate or purify chemical solutions, allowing for the production of high purity chemicals. It has applications in the pharmaceutical, food, and chemical industries.

vi. Recovery of Solvents: Membrane distillation can assist in the recovery of solvents from industrial processes, helping to reduce waste and improve overall process efficiency. It enables the separation and concentration of solvents from solvent water mixtures.

vii. Zero liquid Discharge Systems: Membrane distillation plays a role in Zero Liquid Discharge (ZLD) systems, where it helps concentrate wastewater to the point of complete water recovery, minimizing wastewater discharge and reducing its environmental impact.

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Table 2.2 Basic MD Configurations, its Application Area, Merits, and Demerits.

MD Configuration	Application area	Merits	Demerits
DCMD	• Treatment of dye effluents • Arsenic removal from aqueous solution • Seawater desalination • Crystallization	• Has high permeate flux. • It is considered at commercial scale	• It has a high conductive loss
AGMD	➢ Used in the concentration of fruit juices. ➢ Used in the separation of azeotropic mixtures. ➢ VOC removal	➢ It has a low conductive heat loss. ➢ The Process is simple. ➢ It has a minimal risk of temperature polarization	➢ It has a lower flux relative to DCMD and VMD
SGMD	▪ Brackish water desalination ▪ Used in the separation of azeotropic mixtures. ▪ Used in wastewater treatment. ▪ VOC removal	▪ There is reduction of the barrier to its mass transport through forced flow	▪ Has a high of temperature polarization ▪ Its process is complex

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VMD	Seawater distillation Used in the treatment of alcoholic solution. Used in the recovery of aroma compounds. Used in the treatment of textile wastewater	Has a high permeate flux. It is considered at commercial scale.	Has an elevated risk of membrane pore wetting. Its process is complex

(Source: Ali *et. al*., 2018; Alklabi and Lior, 2005a; Alkhudhiri *et. al*., 2012; Al-Obaidani *et. al*., 2008))

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2.18.5 The Concept of Thermal Performance in MD Technology

The ratio of the latent heat of vaporization to the total (latent and conduction) heat can be used to define the Thermal Efficiency (TE) in MD. The thermal efficiency of an MD system is considered as an effective tool in the measurement of the desired thermal transport that is local to some membrane multilayer that are sandwich which comprises the membranes and as well as the main channels (Swaminathan *et. al*., 2018). A study (Al-Obaidani *et. al*., 2008) noted that raising feed temperature, feed flow rate, and membrane thickness can all increase thermal efficiency. However, the thermal efficiency drops with an increase in the salt solution's concentration. In the majority of researched DCMD processes, the thermal efficiency varied depending on the membrane thickness from 0.1 to 0.7 mm (Li & Sirkar, 2005; Al-Obaidani *et. al*., 2008; Qtaishat *et. al*., 2008). Relative to DCMD, VMD can achieve higher vapour permeation rates and GOR under the same feed conditions (Li & Sirkar, 2005; Fan & Peng, 2012). By utilizing a strong hydrophobic flat membrane and a symmetric, sponge-like cross-sectional support structure, Fan and Peng (2012) compared the thermal efficiency of DCMD to that of the VMD. They discovered that the VMD process had a higher thermal efficiency than the DCMD process at the same operating temperature. For example, the thermal efficiency of the VMD process varied from 88.1 % to 91.9 % and from 59.6 % to 70.5 % in the DCMD process when the feed temperature was also varied from 50 °C to 85 °C.

However, evacuation and a large condenser capacity are needed for the permeate vapour collection of VMD. Furthermore, because of the significant transmembrane pressure difference that results, membrane wetting, or leakage is also a significant issue.

As AGMD can prevent conductive losses due to the air gap's low thermal conductivity, it has a higher heat efficiency of 0.70 - 0.98. (Banat & Simandl, 1998; Liu *et. al*., 1998). However, the addition of the cooling wall and the air gap complicates the module's construction and raises the mass transfer resistance, which typically results in a lower flux than DCMD for the same driving force (Alklaibi & Lior, 2005).

Using mathematical simulation, a study (Peng *et. al*., 2013) investigated the impact of thermal conductivity on thermal efficiency and permeate flux; the results are as shown in Figure 2.17. According to Al-Obaidani's observations, the simulation revealed that the thermal conductivity increased while the vapour flux and thermal efficiency decreased. The thermal conductivity of the MD membrane (K_m) is a more accurate way to measure

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the effects on the thermal efficiency and the vapour flux than the thermal conductivity of the polymer because it also depends on the effect of the membrane porosity. The permeate flux decreased from 45 to 33 kg/m^2h as K_m increased from 0.01 to 0.05 W/m.K; at the same time, thermal efficiency dropped from 83 to 47 %. Lower thermal resistances were offered by membranes with higher K_m. The temperatures $T_{f,m}$ and $T_{p,m}$ on the membrane surfaces decreased and increased as a result, and the conductive heat flux across the membrane increased. As a result, the permeate flux and the thermal efficiency decreased, as did the driving force and latent heat of vapourization. The MD membranes should have as little thermal conductivity as possible to perform better.

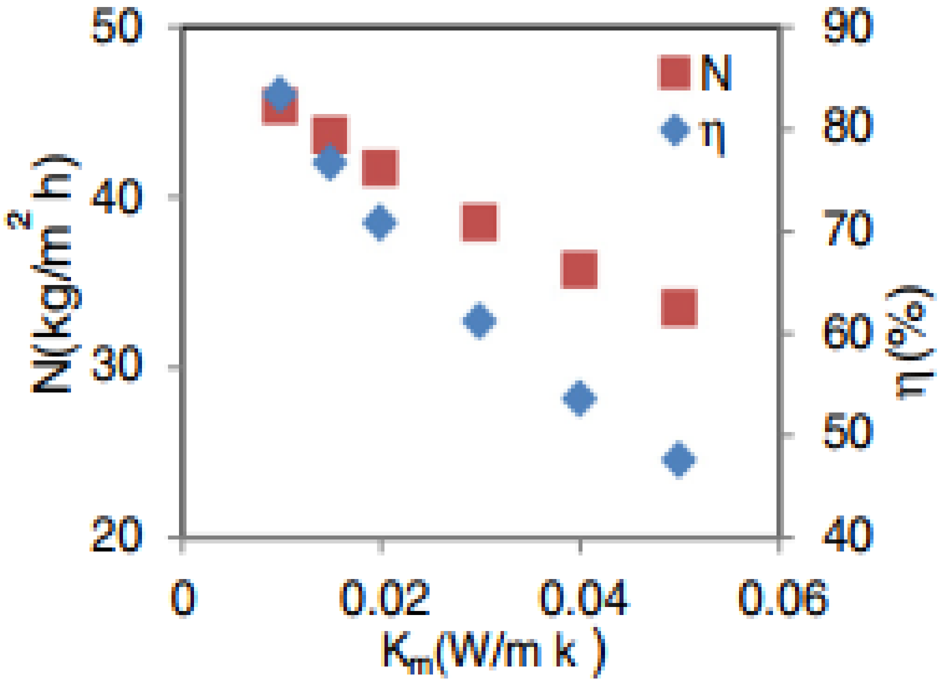

Figure 2.17 A Graph of Thermal Conductivity vs. Thermal Efficiency and Permeate Flux

(Peng *et. al.*, 2013)

In MD processes, heat is transferred across the membrane matrix in two diverse ways: (i) through the membrane matrix's gas through conduction and (ii) through mass transfer using the latent heat of vaporization. Conduction of heat across the membrane is regarded as a heat loss and should be minimized to increase the thermal efficiency of the MD process because there is no flux induced by this conduction.

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According to Fane *et al*., (1987), the transmembrane conduction of heat results in the loss of 20–50 % of the heat generated. Gostoli & Sarti, (1998) demonstrated that if the transmembrane heat conduction rate were too high, the temperature difference between the two sides of the membrane would be nearly zero. In addition, if the pressure on the cold side of the membrane is higher than that on the hot side, a reverse mass transfer may take place.

It is imperative to note therefore, that, the thermal performance of MD technology is dependent on both the operating factors and the properties of the materials used in the manufacture of the MD system. The thermal analysis of an MD system, therefore, offers an opportunity to optimize on the performance of the MD system.

2.19 Technical and Economic Assessment of a Waste Incineration Facility

In the selection of a waste management practice for use at a particular location, aside been technical feasible, it must additionally be economically sustainable. The techno-economic analysis of a waste incineration facility for use at a particular location therefore involves estimating the total power and energy that can be generated from the total amount of waste generation by the various population sizes prevailing at the location of interest and assessing the financial viability of such a project using key economic indicators.

In performing techno-economic assessment on proposed waste incineration facility, the following are some general approaches that can be adopted.

i. Technical assessment: in performing technical assessment of a waste incineration plant, the calculation of waste generation based on population definitions must be defined explicitly. Appropriate relations are used to determine the total power available in the combustible residues in the waste generated by a set of populations in the area or country of interest and the total power that can be produced by the population sizes as defined are determined subsequently.
ii. Economic assessment: in performing economic assessment of waste incineration facilities, two key economic indicators that can be employed are, the Net Present Value (NPV) and Levelized Cost of Electricity (LCOE). The total net present value of costs represents the present value of all costs associated with the energy project

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over its lifetime, including capital costs, operating costs, maintenance costs, and any other relevant expenses.

The total net present value of energy Output represents the present value of all energy generated by the project over its lifetime, taking into consideration the capacity factor (that is the ratio of actual energy generated to maximum possible energy generation).

Dividing the total net present value of costs by the total net present value of energy output, the LCOE provides an estimate of the average cost of producing each unit of energy over the project's lifetime. It is imperative to note however, that the LCOE formula may incorporate additional factors or adjustments depending on the specific characteristics and requirements of the energy project. This may include, tax incentives, government subsidies, and or any other financial considerations.

It must be noted that, for the proposed facility to be economically viable, there are two conditions that must be met (Branker *et. al*., 2011; Rangel 2016).

i. NPV > 0 (additionally the greater the value, the more attractive the venture)
ii. LCOE < tariff for energy sales

2.20 A Brief Geography and Population Distribution of Ghana

Ghana is a country located in West Africa along the Gulf of Guinea. Ghana is bordered by Cote d'Ivoire to the west, Burkina Faso to the north, Togo to the east, and the Atlantic Ocean to the south.

Ghana has a total land area of size of approximately, 238,533 square kilometres and is estimated to have the same land size as Oregon in the USA (Country Reports, 2023). Half of the country is estimated to be less than about 152 metres above sea level, with the highest point to be 883 metres above sea level. Ghana is known for its diverse geography features, which includes coastal plains, hills, and mountains in the interior. The coastline of Ghana stretches for about 539 kilometres along the Gulf of Guinea. Major rivers in Ghana include the Volta, Ankobra, Pra, and Tano rivers.

The climate in Ghana is generally described to be tropical with estimated average temperatures to be between 21 ℃ and 32 ℃ and is characterized by two distinct seasons,

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the wet season (which runs from April to October), and the dry season (which runs from November to March).

The population of Ghana is estimated to be a little over 32 million (Ghana Statistical Services, 2023). The capital and largest city of Ghana is Accra which is situated along the south-eastern coast of the country. Other major cities in Ghana include Kumasi, Sekondi-Takoradi, Tamale, and Cape Coast.

The southern part of Ghana particularly the coastal areas are more densely populated relative to the sparsely populated northern regions of the country. The population in Ghana is predominantly concentrated in the urban and peri-urban areas, with quite a significant rural population that are engaged in agriculture and related activities.

The Ashanti region which has Kumasi as its capital is one of the most populous regions in the country. Other regions with a relatively high population densities includes the Volta, Eastern, Western and Greater Accra regions. Figure 2.18 shows a population distribution of Ghana.

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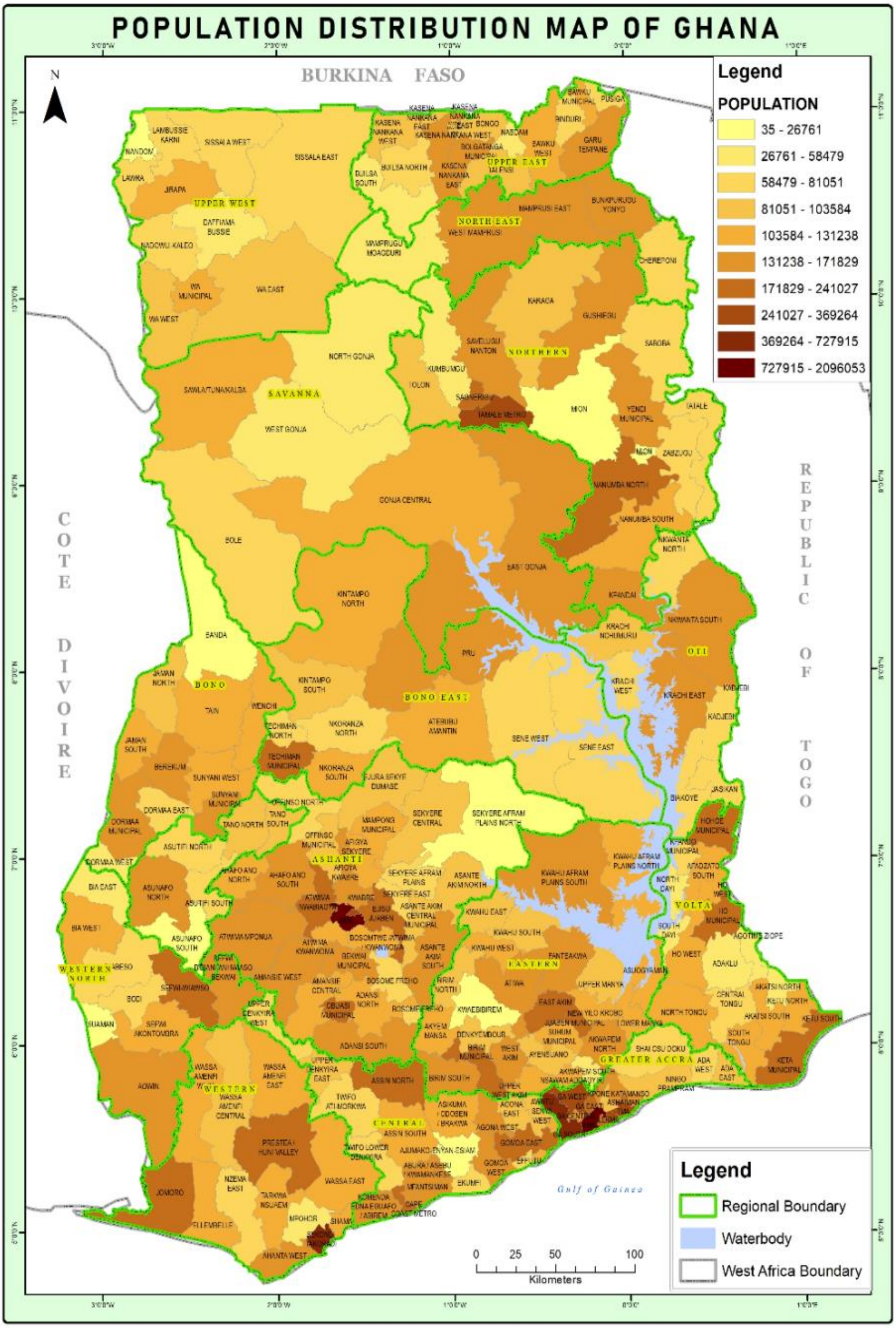

Figure 2.18 A Population Distribution Map of Ghana

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CHAPTER 3

METHOD USED

3.1 Overview

A technical assessment of this work was carried out by determining the power and energy that can be generated from the solid waste generated in Ghana in proposed waste incineration facilities and this was followed up with an economic assessment of these proposed waste incineration facilities. The methods and relations that were used to perform these assessments are presented in this chapter.

The benefits of integrating electricity generation from WtE facilities into the energy mix of a country include the reduction of CO_2 emissions. Therefore, the reduction in CO_2 emissions that can be made by incorporating electricity generation from waste incineration facilities into the energy mix of Ghana was also determined. The method used in determining the CO_2 emissions from the various thermal power plants in Ghana is described in this chapter.

A Membrane Distillation (MD) system was incorporated into the waste incineration plant, and its thermal performance assessed. This was done by modelling and simulating various aspects of the waste incineration plant using Aspen Plus® software (version 11). Figure 3.1 depicts the proposed waste incineration facility.

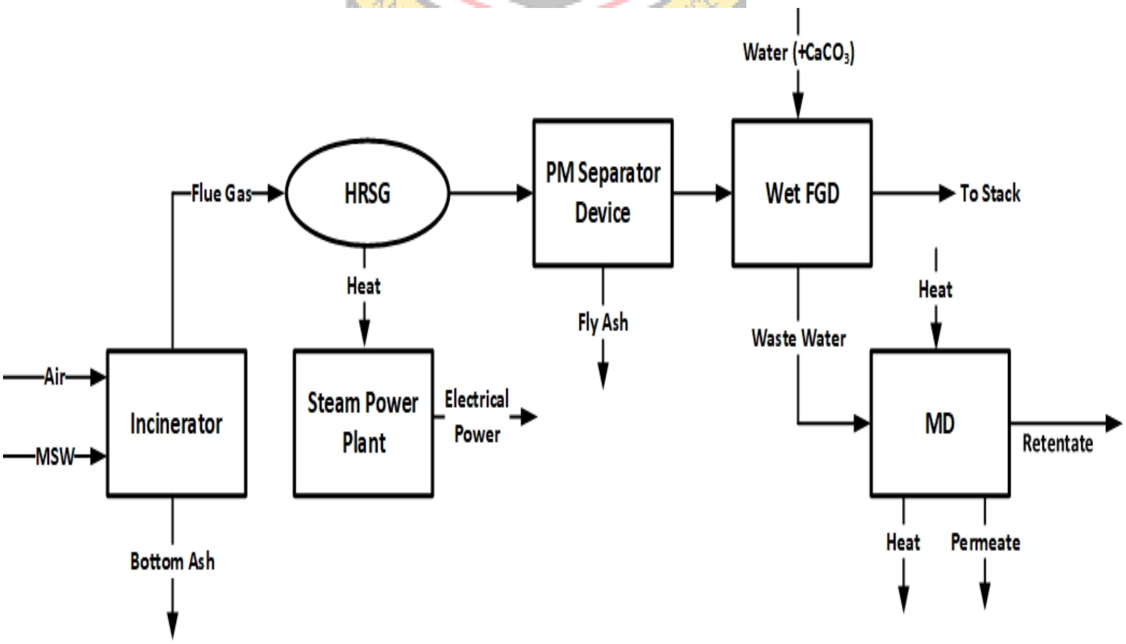

Figure 3.1 Block Flowchart of the Proposed Waste Incineration Plant

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The various models that were simulated are the Waste Incinerator, particulate matter separation device, steam power plant, wet scrubbing, and MD systems.

3.2 Techno-Economic Assessment of Proposed Waste Incineration Plant

To perform a techno-economic assessment of the waste incineration facility proposed for use in Ghana, the following methods were used, technical assessment, and economic assessment.

3.2.1 Technical Assessment

In performing the technical assessment of the waste incineration plant, the Calculation of waste generation based on population sizes are defined explicitly. Energy calculations are used to determine the total power available in the combustible residues in the waste, and the total power that can be produced by the waste incineration plant are also determined subsequently.

Calculation of Waste Generation Based on Population Definitions:

Calculations were performed for 15 sets of population sizes data (1 000, 2 000, 5 000, 10 000, 25 000, 50 000, 100 000, 150 000, 200 000, 300 000, 500 000, 1 000 000, 1 500 000, 2 000 000, and 3 000 000), which was established based on the population limits of population sizes defined in the national population distribution (Figure 2.18).

Calculation of the Total Waste Generation for each Population Size

The total waste generation per day for each population size is the first step of calculation. This was calculated using equation 3.1.

$$W_T = \frac{P_t . W_P}{1000} \tag{3.1}$$

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Where, W_T is the waste production (tonne/day), P_t is the total population as defined earlier, W_P is the per capita waste generation index (measured in kg/person/day), which is 0.47 as contained in the study by Mieza *et. al.*, 2015.

The total production of each type of waste residue in each analysed population was also calculated using equation 3.2.

$$W_i = W_T F_i \quad (3.2)$$

Where, W_i is the daily production of each type of MSW residue, and F_i is the fraction of each of MSW residue as obtained from the gravimetric composition of waste from Ghana (Mieza *et al.*, 2015).

Calculation of Available Power and Energy in the Combustible Waste Residues

The energy calculations are based on the heat-generating values that can be derived from each type of residue present using equation 3.3 (FEAM, 2012) Where, LCV_{ex} is the lower calorific value of each type of waste residue measured in kCal/kg as determined from experimental studies and these are shown in Table 3.1, R_1 is a conversion constant which converts kCal/kg to kJ/kg and is given as 4.184, LCV_i is the calorific value contained in each fraction in kJ/kg,, and the total heat values can be calculated using equation 3.4 (Santos *et. al.*, 2019).

The available power in the combustible residue was calculated using equation 3.5 (Leme *et. al.*, 2014) where, η is the electricity recovery of all energy generation system from incineration, R_2 is a unit adjustment constant such that the resulting power is in kW (given as 0.01157) and the energy that can be produced in the incinerator was subsequently calculated using equation 3.6 (Santos *et. al.*, 2018). Where, C_F is the capacity factor adopted to be 80% (FEAM, 2012), the 8760 is equal to the number of hours of operation of the incinerator per year.

$$LCV_i = LCV_{ex}.F_i.R_1 \quad (3.3)$$

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$$LCV_T = \sum_{i=1}^{n} LCV_i \quad (3.4)$$

$$P = LCV_T.\eta.W_T.R_2 \quad (3.5)$$

$$E = P.C_F.8760 \quad (3.6)$$

Table 3.1 Specific Lower Calorific Values of various Components of MSW.

MSW Component	Lower Calorific Value on Wet Basis (kCal/kg)
Organics	712
Paper	2 729
Textile	1 921
Plastic	8 193
Rubber	8 633

(Source: FEAM, 2012)

3.2.2 Economic Assessment

The initial investment cost of the waste incineration facility was calculated as a function of the electrical power generated in the waste incinerator in kW using equation 3.7 (Gomez *et. al*., 2010), and the NPV values was also calculated using equation 3.8.

$$I = 15\,797\,P^{0.82} \quad (3.7)$$

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$$NPV = \sum_{t=1}^{m} \frac{(E.tf) - C_{om}}{(1+i)^n} - I \qquad (3.8)$$

Where, tf is the energy sales tariff in US$$/kWh., C_{om} is the operating and maintenance cost per year, which was adopted to be 4 % of the initial cost of investment in US$ (Gomez *et. al*., 2010), m is the project life (which is taken to be 25 years in this study), n is the year of analysis, i is interest rate which was taken to be 12.5 %.

The tf used in this assessment was 0.1462 US$/kWh according to the Public Utilities Regulatory Commission of Ghana which the tariff for waste-to-energy feed-in tariff for waste to energy electricity generation in 2021.

$$LCOE = \frac{\sum_{t=1}^{m} \frac{C_n}{(1+i)^n}}{\sum_{t=1}^{m} \frac{E_n}{(1+j)^n}} \qquad (3.9)$$

Where, C_n is the total cost of the enterprise, which includes the investment cost (which is a one-time cost, which was determined earlier using equation 3.7), maintenance and operational cost of the facility per year (which is the same as was adopted earlier). The E_n is the total energy produced per year of the facility, and j is the degradation of the waste incineration facility which was taken to be 1 % in this study.

3.3 Determination of the total CO_2 emissions from Thermal Power Plants in Ghana

This section explains how the total CO_2 emission from the fifteen (15) thermal power plants operating in Ghana was determined. To achieve this, there was the need to determine the amount of electricity generated by each plant and the carbon intensity of the fuel source used to generate electricity from each plant. The following general approach was used.

i. Gathering of data on the total electricity generation from all the installed thermal power plants that are operating in Ghana over a given period of time (the period considered in this case, is one year). Table 3.3 list the thermal power plants (including their power output) that are currently operating in Ghana.

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ii. Determination of the carbon intensity of the fuel source use to generate the electricity at each thermal power plant. The carbon intensity of the fuel can be expressed as the amount of CO_2 per kWh of electricity generation. Table 3.2 list the carbon intensity of some selected fuels used in thermal power plants.

iii. Calculate the total CO_2 emissions from each thermal power plant by multiplying the electricity generation by the carbon intensity of the fuel source.

iv. Sum up the total CO_2 emissions from all the thermal power plants operating in Ghana to get the total minimum CO_2 emissions for a year.

It is worth noting, however, that the actual CO_2 emissions from the thermal power plants may be higher than the emissions as calculated using this approach as there may be additional emissions from sources such as the mining and transportation of the fuel sources. Additionally, in determining the CO_2 emissions from the thermal power plants operating here in Ghana, information on the energy source of all the thermal power plant could not be obtained, as such natural gas was adopted as the source of fuel (natural gas has the lowest carbon intensity among the various fuel sources used in Ghana) for such thermal power plants.

Table 3.2 The Specific CO_2 Emissions of Fuels used in Thermal Power Plants.

Fuel type	**CO_2 emissions ($kgCO_2/kg_{fuel}$)**	**CO_2 emissions ($kgCO_2/kWh$)**
Natural gas	2.75	0.18
Diesel	3.15	0.22
Coal	3.37	0.37
Heavy fuel oil	3.11	0.27
LPG	3.01	0.22

(Source: EIA, 2022)

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Table 3.3 List of Thermal Power Plants operating in Ghana.

Thermal Power Plant	Power Output (MW)
Takoradi Power Company (TAPCO)	330
Takoradi International Company (TICO)	340
Tema Thermal I Power Plant (TT1PP)	110
Tema Thermal 2 Power Plant (TT2PP)	87
Cenit Energy Ltd	110
Kpone Thermal Power Plant	220
Ameri Plant	250
Sunon Asogli Power (Ghana) Ltd	560
KarPowership	470
Trojan	44
Amandi	203
AKSA	370
CenPower	360
Early Power/Bridge	144
Genser	155

(Source: Energy Commission, 2020)

KNOWLEDGE, TRUTH AND EXCELLENCE

3.4 Modelling and Simulation

The integrated system is divided into four subsystems that were simulated using Aspen Plus®. The four subsystem models simulated in this study are described as follows;

Firstly, the waste incineration plant model is simulated to determine the temperature of the flue gases that exits the waste incinerator, the volume of emissions (volumetric flow rate of flue gases exiting the incinerator), as well as flow rates of the various constituents of the flue gas. The waste incineration plant model is the same model that was used in the particulate matter (PM) separation assessment.

The second model is the steam power cycle. This cycle is used to determine the quantum of electricity that can be generated after waste heat recovery. The basic Rankine cycle

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operating in condensing mode (electricity generation only) is adopted, since only electricity generation is the desired output of a waste incineration plant which will be operating in a tropical country like Ghana.

The third model is the wet scrubbing process (the wet flue gas desulphurization method), was simulated to determine the volume of water needed to clean acid gases (limited to only HCl and SO_2 in this study) from the flue gas stream and subsequently the volume of flue gas condensate (wastewater) generated in the process.

The fourth model is the MD system which is adopted to treat the flue gas condensate produced during the acid gas cleaning. A thermal performance analysis was carried on the MD system and the relations used in these analyses are also presented.

3.4.1 Block Flowchart of the Proposed Waste Incineration Plant

The integrated system block flow chart for the proposed waste incineration plant used in this research is depicted in Figure 3.1. MSW are first fed into the incinerator/boiler, where sufficient air is added to aid in complete oxidation of the MSW. After combustion of the MSW in the incinerator/boiler, the flue gas (which carries with it a high energy and particulate matter) and ash are produced. While ash is collected at the bottom, the flue gas stream exits into a Heat Recovery Steam Generator (HRSG). After heat exchange with high pressure water to produce high pressure steam, the flue gas is cooled down further (to 160°C) before entering a particulate matter (PM) separation device. At this stage, PM is separated from the flue gas stream using either a cyclone, filter bag, electrostatic precipitator PM separation device or a combination of them. The flue gas stream then goes into the wet FGD where water and aqueous calcium carbonate ($CaCO_3$) are added to clean out acidic gases. The flue gas stream is further cleaned before its release to the environment through a stack. The produced wastewater after acid gas cleaning, on the other hand, is sent to the MD system for treatment prior to reuse or disposal into the environment. The wastewater that goes into the MD system is treated, and produces a cleaned water (Permeate), and the captured solids and the remains in the concentrate (Ret) can be returned to the MD system for further cleaning or disposed.

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3.4.2 Model of the Waste Incineration Plant

In the waste incineration plant, the wet MSW (WET-MSW) is sent into a vessel (DRY-REAC), where hot air (HOTAIR) is mixed with WET-MSW. A calculator block is defined in Aspen plus to control the drying process in another vessel (DRY-FLSH) and the by-products from this vessel are a dry MSW (DRY-MSW) and an exhaust vapour (EXHAUST), which is discharged into the atmosphere.

DRY-MSW is now ready to be combusted. As its composition can vary based on the source and regional factors (e.g., topography, seasons, food habits…), it has been defined as non-conventional in the model. Consequently, for successful simulation of combustion process, DRY-MSW first needs to be defined based on its content. Therefore, an extra vessel (DECOMP) is included in the flowsheet where DRY-MSW is broken down into its various elemental constituents (Q-DECOMPOST). Q-DECOMPOST is then sent into the combustion chamber (BURN), where sufficient air (ATM-AIR) is added to have a complete oxidation of the MSW. Energy is recovered from the flue gases (CPROD-H) from the combustion process in the heat exchanger (HRSG) for the generation of superheated steam (HPSTEAM) which turns a steam turbine (ST-TURB) for the generation of electrical power (WT-TURB). After the recovery of heat energy from CPROD-H, there is a drop in temperature in the flue gas (CPROD-C) before entering particulate matter (PM) separation devices. In the model depicted in Figure 3.2, all three types (cyclone, bag filter and the electrostatic precipitator (ESP)) of PM removal devices are incorporated. The flue gas stream after the PM separation (ESP-GAS) then goes into the wet scrubbing system for cleaning of acidic gases. Figure 3.2 is a diagram of a waste incineration Aspen Plus® model flowsheet.

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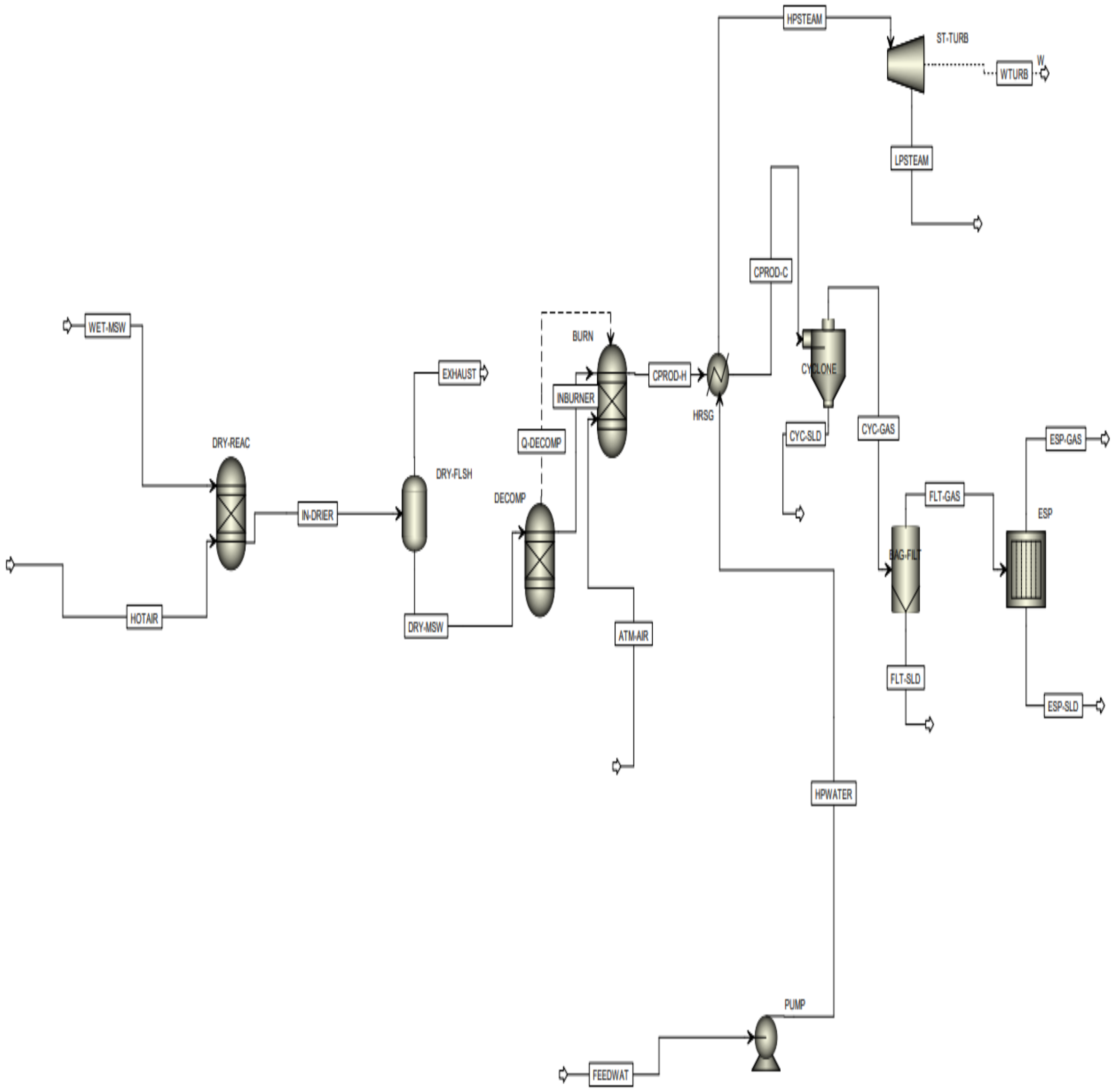

Figure 3.2 Waste Incineration Aspen Plus® Model Flowsheet

The operating parameters of the various streams and blocks used in the model are specified before simulation. The streams in the model that were specified are (i) WET-MSW, (ii) HOTAIR, (iii) DRY-MSW, (iv) ATMAIR. In addition, the proximate and ultimate analysis of the DRY-MSW is provided in the Proxanal, Ultanal, and Sulfanal sections in the model.

The operating parameters of the blocks that were specified before simulations are (i) BURN, (ii) DECOMP, (iii) DRYFLASH, and (iv) DRY REACTOR. Table 3.4 list the operating parameters of the streams that are used in the simulation of the waste

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incineration model, Table 3.5 lists the proxanal, ultanal, and sulfanal of the MSW used in the simulation, and Table 3.6 lists operating parameters of the various blocks that are used in the simulation of the waste incineration plant model. A detailed input data for the various composition of the MSW and results from the waste incineration plant simulations is presented in Appendix D.

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Table 3.4 Parameters of the Streams used in the Simulation of the Waste Incineration Plant Model

Stream	Pressure (bar)	Temperature (°C)	Mass Flow Rate (kg/h)	Heat of Combustion (kJ/kg)
WET-MSW	1.01	-	5000	-
HOTAIR	1.01	200.0	1000	-
ATMAIR	1.01	25.0	1000	-
DRY-MSW	1.01	25.0	10 000	7200

Table 3.5 Proximate and Ultimate Analysis of the MSW used in the simulating the Waste Incineration Plant Model

Proxanal		Ultanal		Sulfanal	
Element	**Value (%)**	**Element**	**Value (%)**	**Element**	**Value (%)**
FC	40.1	Ash	8.4	Pyritic	0.5
VM	51.5	Carbon	67.9	Sulphate	0.1
Ash	8.4	Hydrogen	4.8	Organic	0.7
Moisture	50.0	Nitrogen	1.1		
		Chlorine	0.1		
		Sulphur	1.3		
		Oxygen	16.4		

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Table 3.6 Parameters for the Various Blocks that were used for the Simulation of the Waste Incineration Plant Model

Block	Pressure (bar)	Temperature (°C)	Heat Duty (kJ/kg)
BURN	1.01	-	-
DECOMP	1.01	25.0	-
DRY-FLSH	1.01	-	0.0
DRY-REAC	1.01	-	0.0

3.4.3 PM Separation

In performing the technical assessment of PM separation, the same model for waste incineration was used, however, with different arrangement of the PM devices. The devices were incorporated in the model for the assessment as follows, (1) cyclone only (2) fabric filter only (3) ESP only (4) Cyclone and ESP (5) Fabric filter and ESP and (6) Cyclone, fabric filter and ESP. The particles size ranges that were used in the study are 0.0 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.5 µm, 7.5 – 15.0 µm, 15.0 – 26.0 µm.

The flue gases are usually cooled before PM separation, this is usually done to control the production of certain unwanted gases that are produced during combustion of the MSW. A parametric analysis was therefore, performed to assess the effect of cooling of the flue gases on the separation efficiencies of the PM separation devices. The temperature was lowered from 440 °C to 240 °C, and subsequently from 240 °C to 120 °C during the parametric analysis.

A detailed design of the cyclone, fabric filter, and ESP PM separation devices that were used in the study are presented in Appendix A, B and C, respectively.

3.4.4 Electricity Generation from the Waste Incineration Plant

The electricity generation from the waste incineration plant is achieved by the production of steam by the incorporation of a heat recovery steam generator (HRSG). The steam

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generated is used to turn a steam turbine in a Rankine cycle operating in condensing mode (electricity generation only). The steam cycle or Rankine cycle is a cycle where the working fluid (water in this case) passes through four basic processes, including an adiabatic/isentropic compression, an isobaric (constant pressure) heat addition which is also referred to as superheated steam formation, adiabatic/isentropic expansion (power generation) and an isobaric heat rejection (heat recovered) for a steam turbine-based CHP.

Model of the Steam Power Plant

Figure 3.3 is an Aspen Plus® model flowsheet of a Rankine cycle used for electrical generation. This model is used to determine the maximum electrical power that can be generated when heat is recovered from the waste incineration plant via a HRSG. The base method used in Aspen plus for the steam cycle is IAPWS-95. Low pressure water (LPWATER) is sent into the pump (PUMP), where the pressure on the water is increased. The high pressure water (HPWATER) is sent into the boiler (BOILER), which is a heat exchanger in the combustion model (the HRSG) and this is where heat is recovered to generate steam. The generated high pressure steam (HPSTEAM) is expanded in a steam turbine (S-TURB), where the blades on the steam turbine are turned for the generation of electricity only (condensing mode operation).

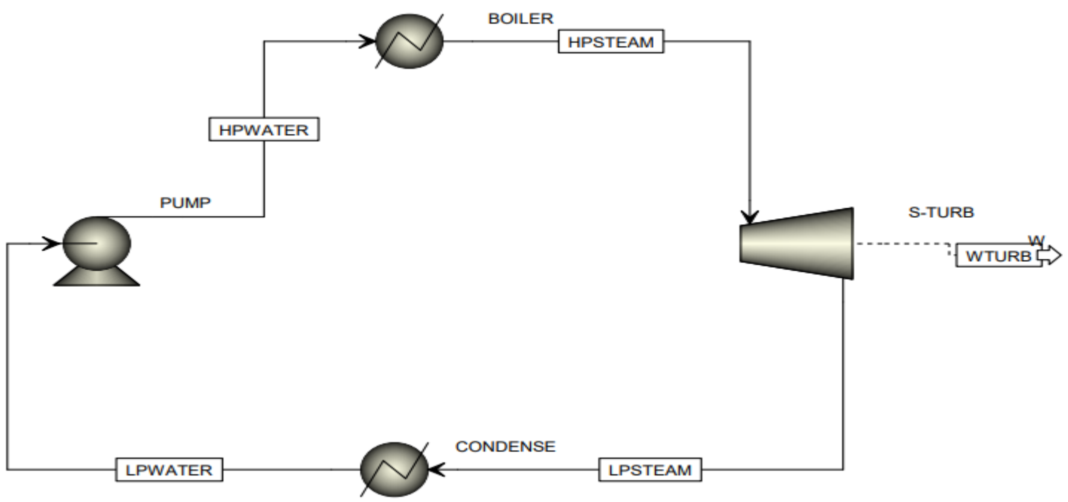

Figure 3.3 A Steam Cycle Aspen Plus® Model Flowsheet

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Table 3.7 list the operating parameters of the various blocks that were used simulation of the steam power cycle model. The incorporated pump used in pumping the water had a pumping efficiency of 0.90. The turbine type is isentropic with an isentropic efficiency and mechanical efficiency of 0.97. A detailed input data and results obtained from the steam power plant model is presented in Appendix E.

Table 3.7 Data of the Blocks that were used in the Steam Power Cycle Model Simulation

Block	Pressure (MPa)	Discharge Pressure (MPa)	Temperature (°C)	Valid Phase
BOILER	4.0	-	600.0	Liquid-vapour only
PUMP	-	4.0	25.0	-
CONDENSER	0.1	-	-	Liquid only
TURBINE	-	0.1	-	-

3.4.5 Model of the Wet Scrubbing Process

An Aspen Plus® model flowsheet (Figure 3.4) of a wet scrubbing process was developed to simulate the cleaning process of acid gases from produced flue gas in the previous model. The main output of this model was to determine the amount of flue gas condensate (wastewater) that would be generated. The base method used in Aspen Plus® is ELECNRTL.

As can be seen in Figure 3.4, the developed model has two stages. RadFrac (WTSCRUB1) from Aspen block built in library, which is the acidic scrubber, is selected where the flue gas stream from the waste incinerator (GASFEED) and water (LIQFEED1) are the feed streams. The products then are wastewater (LIQPROD1), and the flue gas stream

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(GASPROD1). The second wet scrubber (WTSCRUB2), selected same as the first scrubber in Aspen plus, is the alkaline (or neutral) scrubber with two feeds: the partially cleaned flue gas (GASPROD1) from WTSCRUB1 and a liquid feed (LIQFEED2). The latter is an alkaline solution, which in this study calcium carbonate ($CaCO_3$) is used. Table 3.8 list the operating parameters used in the simulation of the wet scrubbing model.

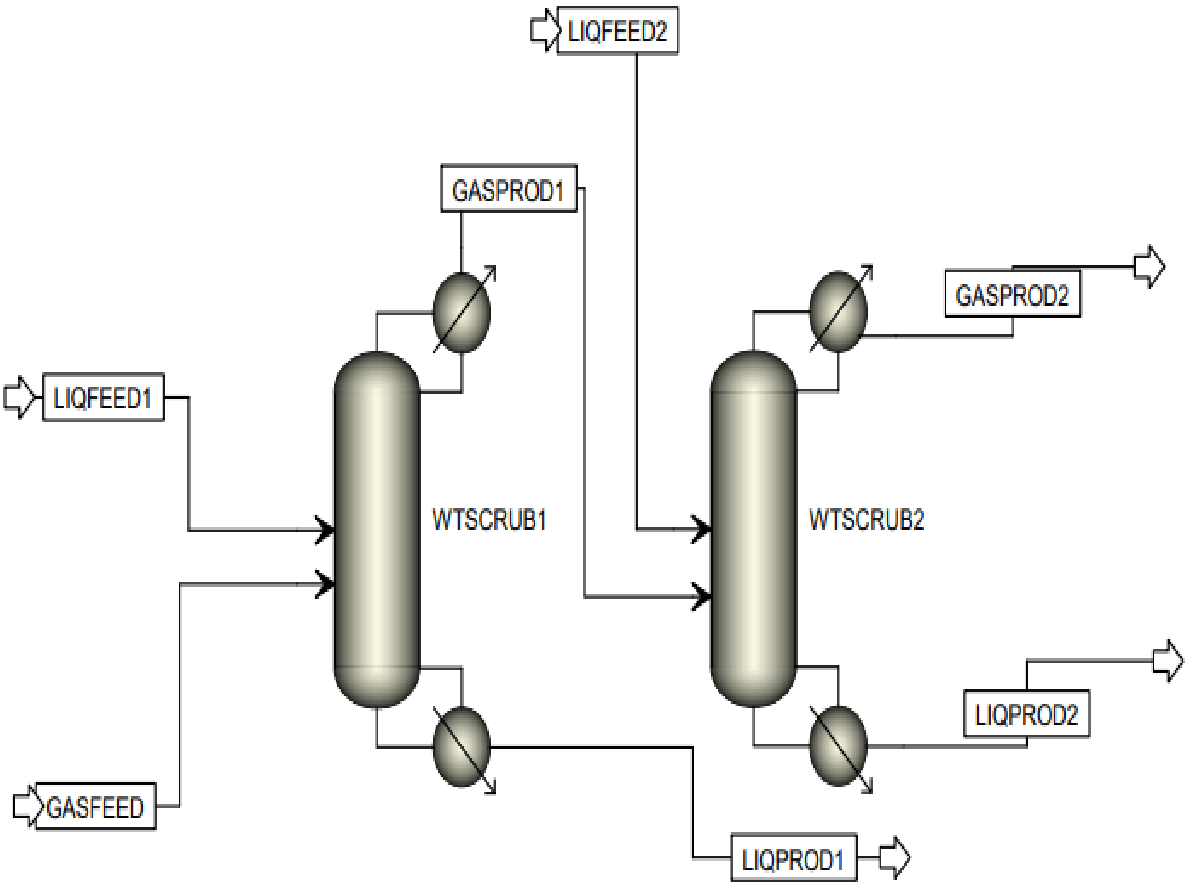

Figure 3.4 A Wet Scrubbing Process Aspen Plus® Model Flowsheet

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Table 3.8 Operating Parameters of the Wet Scrubbing Process

Parameter	Value
Flue gas feed temperature to WTSCRUB1	160 °C
Flue gas feed pressure to WTSCRUB1	1.01 bar
Liquid feed temperature to WTSCRUB1	30 °C
Liquid feed pressure to WTCSCRUB1	1.5 bar
Operating Pressure in WTSCRUB1	1.01 bar
Number of stages in WTSCRUB1	10
Liquid feed temperature to WTSCRUB2	35 °C
Liquid feed pressure to WTSCRUB2	1.5 bar
Number of stages in WTSCRUB2	10

3.4.6 Incorporation of an MD Technology into the treatment of Wastewater

A novel MD system which is incorporated into the waste incineration plant to treat the wastewater that is produced after cleaning the flue gases out of the acidic gases via wet scrubbing process.

Model of the MD system

There are no available blocks in the Aspen plus built-in library that can readily be used in simulation of an MD unit. Hence, it was modelled using a customized USER Model2 in Aspen plus. An excel file sheet built-in Aspen plus was modified with data obtained from the simulation of the wet scrubbing model. Table 3.9 depicts the operating parameters used in the simulation of the MD system. This simulation work is based on a similar MD system (Noor *et al.*, 2020). However, there are some few differences between that simulation work and this current work. The current model has a single air gap MD module relative to the dual-cascaded MD modules used in that work. There are also differences in parameters such as the feed inlet temperature, coolant inlet temperature, density of the feed and the composition of the flue gas condensate. The feed and coolant inlet pressures, however, remain the same. Figure 3.5 (a) –(c) shows the Xzero Laboratory Prototype,

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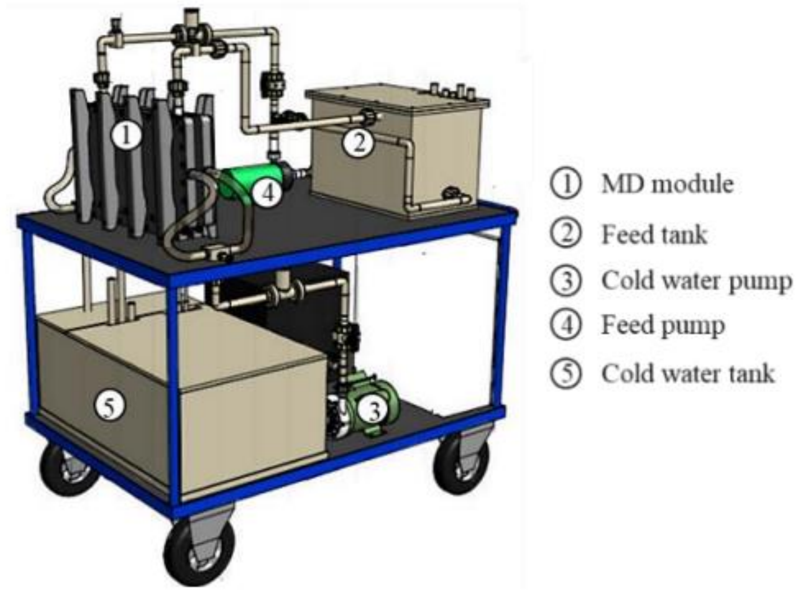
Xzero pilot-scale unit, and the schematic flow diagram of AGMD separation process respectively of the experimental MD set up process of the experimental research work carried out by Noor (2021). The Xzero pilot plant was built in a joint project between IVL Swedish Environmental Research Institute and KTH Royal Institute of Technology, Stockholm, Sweden. The Air Gap Membrane Distillation (AGMD) modules which employ PTFE membranes (with PP as back support material) are considered in both facilities.



(a)

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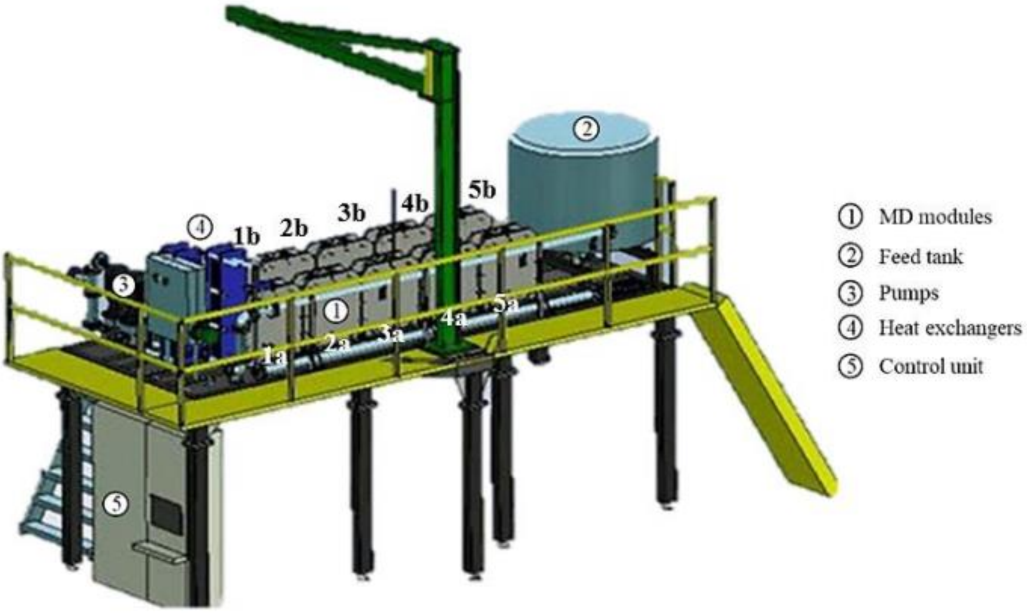
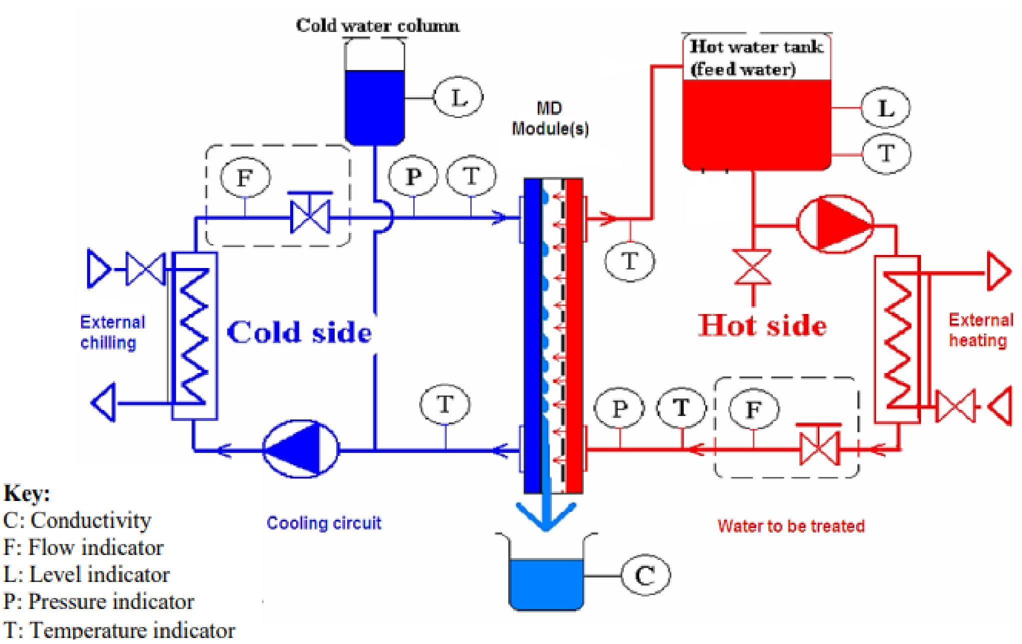


(b)



(c)

Figure 3.5 Experimental Set up of the AGMD (a) Xzero Laboratory Prototype (b) Xzero Pilot-Scale Unit (c) Schematic Flow Diagram of AGMD Separation Process

(Source: Noor, 2021)

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The Aspen Plus® MD model flowsheet is shown in Figure 3.6 and the base method used for this model is IDEAL. The flue gas condensate or wastewater (WWSCRUB) generated from the wet scrubbing process is collected into a tank (TNK) at a temperature of 56.7 °C. The wastewater stored in the tank (FD1) is then passed through a heat exchanger (HX) and heated up to a temperature of 85°C using heat from cooling of the flue gas stream (from 440 °C to 160°C) before particulate matter separation. The heated flue gas condensate (FD2) then goes into the MD module (MD). The temperature of the flue gas stream drops because of the latent heat of vaporization which corresponds to the permeate flux passing through the membrane. The concentrate and permeate streams from the MD module are referred to as RET and PERM, respectively. The treated water (PERM) is then collected into another tank for reuse.

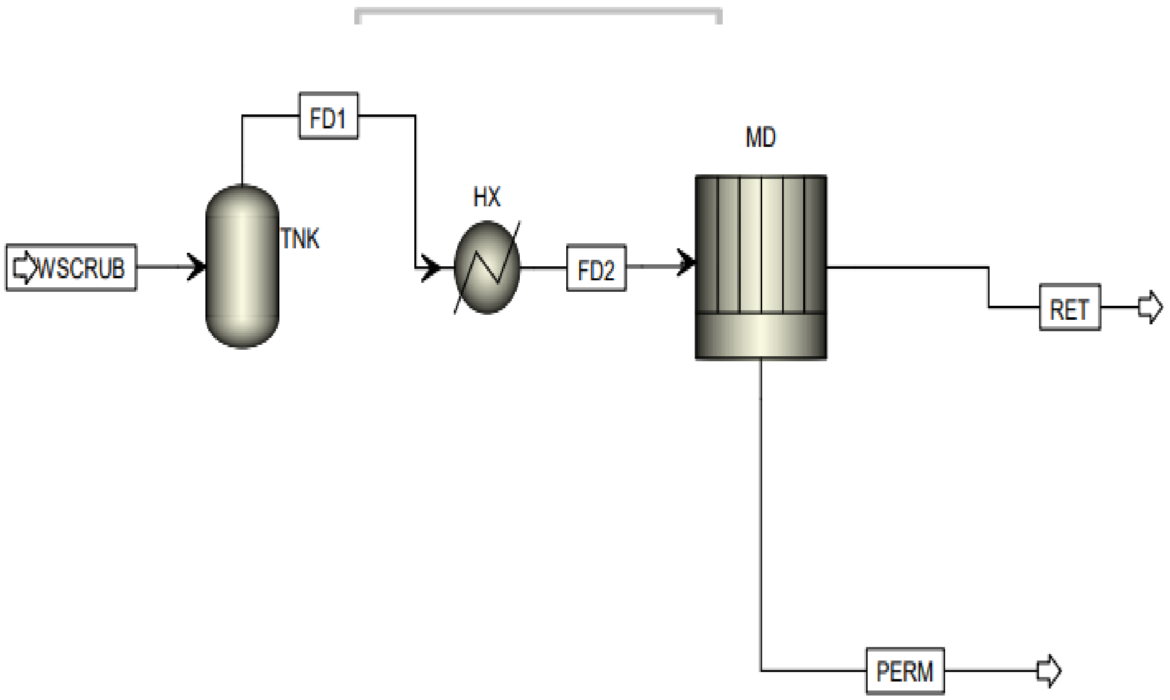

Figure 3.6 MD System Aspen Plus® Model Flowsheet

During the simulation of the MD system, the coolant stream is considered water to be pumped from the surroundings (e.g., from a river) with an ambient temperature of between 25 °C to 27 °C (the ambient temperature of water in Ghana).

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Table 3.9 Operating Parameters for the MD System

Operating Parameter	Value
Feed flowrate	1500 l/h
Feed inlet temperature	85 ℃
Feed inlet pressure	1.0 bar
Coolant flowrate	1500 l/h
Coolant inlet temperature	26 ℃
Coolant inlet pressure	1.01 bar

Thermal Energy Analysis of the MD system

The permeate flux, or simply flux, of an MD (J_p) is considered as the most relevant metric used in the assessment of any membrane technology. It is defined as the flow rate of permeate flowing through the membrane measured in kg/m^{2}s and can be expressed mathematically using equation 3.10 (Swaminathan, 2018).

$$J_p = \frac{\dot{m}_p}{A} \tag{3.10}$$

Where, $\dot{m}_p$ is the mass flow rate of the permeate measured in kg/s and A is the effective membrane area measured in m^2.

The Thermal Efficiency (TE) or evaporative thermal efficiency of MD systems is defined as the ratio of the latent heat of vaporization to the total (latent and conduction) heat. The TE of MD systems is considered as an effective tool in the measurement of desired thermal transport. It can be expressed mathematically using equation 3.11 (Swaminathan *et. al*., 2018).

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$$TE\ (\%) = \frac{\dot{m}_p \Delta H_{v,w}}{Q_m} \times 100 \tag{3.11}$$

Where, $\Delta H_{v,w}$ refers to the enthalpy of vaporization of the water in kJ/kg, and Q_m is the total heat flux through the membrane in kW which can be determined by using equation 3.12.

$$Q_m = \dot{m}_f C_p\ (T_{f,in} - T_{f,out}) \tag{3.12}$$

Where, $\dot{m}_f$ refers to the feed mass flow rate measured in *kg/s*, C_p refers to the feed water specific heat measured in *kJ/kg ℃*, while $T_{f,in}$ and $T_{f,out}$ refers to the inlet and outlet feed water temperatures respectively measured in *℃*.

Another important parameter for evaluation of the thermal performance of an MD system is Specific Energy Consumption (SEC). It is defined as the energy required to produce 1 m^3 of distillate water in MD systems and can be determined using equation 3.13 (Soomro & Kim, 2018).

$$SEC\left(kWh/_{m^3}\right) = \left[\frac{Q_m \rho}{J_p A}\right]/3600 \tag{3.13}$$

Where, ρ refers to the density of water measured in kg/m^3.

Gained Output Ratio (GOR) is defined as the ratio of thermal energy that is required to produce distillate water in an MD system to the energy input to the system. GOR, a dimensionless parameter can be expressed mathematically using equation 3.14 (Khayet, 2013).

$$GOR = \frac{J_p A \Delta H_{v,w}}{E_{in}} \tag{3.14}$$

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Where, E_{in} refers to the total power input to the system measured in kW.

Other parameters that are also determined are the total required area (denoted $A_{m,T}$), and total number of membranes required (denoted N_T)

The total required area of membranes that is required to produce the desired yield was estimated considering the reference membrane and the related permeate flow rate using equation 3.15.

$$A_{m,T} = \dot{m}_{p,T} \frac{A_m}{\dot{m}_p} \tag{3.15}$$

Where, $\dot{m}_{p,T}$ is the desired product yield and $\dot{m}_p$ is the reference permeate flow rate.

The total number of MD modules required is also estimated using a ratio of total required area to the reference membrane area. Equation 3.16 is used to determine the total required area.

$$N_T = \frac{A_{m,T}}{A_m} \tag{3.16}$$

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CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Overview

This chapter presents the results and discussions on the techno-economic assessment for the proposed waste incineration facility for use in Ghana. The results obtained after simulating the PM separation, steam power plant, wet scrubbing, and MD system models are also presented and discussed.

4.2 Results from the Technical Assessment

The results from the technical assessment of the waste incineration plant are presented in this section. The annual power (in kW) and energy (in MWh/year), that can be produced from the various population size distributions as was determined earlier using equations 3.5 and 3.6 respectively, are presented in Table 4.1. It can be observed that with a population of 3,000,000 inhabitants the installed waste incineration capacity was 35.81 MW and energy production of 250,940.06 MWh/year of electricity, which is capable of supplying electricity to meet the electricity demand of about 630,000 inhabitants in Ghana per year (although the average electricity demand can vary depending on factors such as location, income level, household size, and lifestyle with the average per capita electricity energy demand in Ghana estimated to be 399.22 kWh/year (Worlddata, 2023). With a population of 1,000,000 inhabitants, the installed waste incineration capacity was 11.94 MW and energy production of 83,646.69 MWh/year, which is capable of supplying electricity to meet the electricity demand of about 200,000 inhabitants in Ghana per year.

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Table 4.1 Power and Energy Production

Population (Inhabitants)	Waste Generation (t/d)	Power (kW)	Energy (MWh//year)
1 000	0.47	11.94	83.65
2 000	0.94	23.87	167.29
5 000	2.35	59.68	418.23
10 000	4.70	119.36	836.47
25 000	11.75	298.40	2 091.17
50 000	23.50	596.79	4 182.33
100 000	47.00	1 193.59	8 364.67
150 000	70.50	1 790.38	12 547.00
200 000	94.00	2 387.18	16 729.34
300 000	141.00	3 580.77	25 094.01
500 000	235.00	5 967.94	41 823.34
1 000 000	470.00	11 935.89	83 646.69
1 500 000	705.00	17 903.83	125 470.03
2 000 000	940.00	23 871.77	167 293.38
3 000 000	1 410.00	35 807.66	250 940.06

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4.3 Results from the Economic Assessment

The economic assessment of the waste incineration plant is presented in this section. The results presented in Table 4.2, are the investment cost (in US$), the operating and maintenance cost (in US$/year), revenue from the sales of electricity (US$/year), the NPV (US$), the LCOE (US$/kWh), and the unit cost (US$/kW) for the waste incineration plant for the various population size definitions. Figure 4.2 shows a graph of the installed capacity of the proposed waste incineration facility against the LCOE.

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Table 4.2 The Investment Cost, Operating and Maintenance Costs, Revenues, NPV, LCOE, and Unit Cost for Proposed Waste Incineration Facility for use in Ghana.

Population (Inhabitants)	Investment Cost (US$)	Operating and Maintenance Cost (US$/year)	Revenues (US$/year)	NPV (US$)	LCOE (US$/kWh)	Unit Cost (US$/kW)
1 000	120,668.92	4,826.76	12,229.15	-64,566.17	1.62	10,109.76
2 000	213,029.64	8,521.19	24,458.29	-92,242.20	1.32	8,923.91
5 000	451,596.78	18,063.87	61,145.73	99,134.09	1.10	7,567.04
10 000	797,251.67	31,890.07	122,291.46	112,099.08	1.01	6,679.45
25 000	1,690,076.03	67,603.04	305,728.64	114,679.09	0.92	5,663.85
50 000	2,983,670.36	119,346.81	611,457.29	746,037.69	0.81	4,999.50
100 000	5,267,389.53	210,695.58	1,222,914.58	2,404,223.34	0.72	4,413.07
150 000	7,344,974.10	293,798.96	1,834,371.87	4,331,035.63	0.63	4,102.46
200 000	9,299,081.04	371,963.24	2,445,829.15	6,418,759.09	0.52	3,895.43
300 000	12,966,861.28	518,674.45	3,668,743.73	10,907,529.58	0.44	3,621.25
500 000	19,712,914.56	788,516.58	6,114,572.89	20,653,292.83	0.40	3,303.13
1 000 000	34,801,297.50	1,392,051.90	12,229,145.77	47,333,091.25	0.32	2,915.69
1 500 000	48,527,762.61	1,941,110.50	18,343,718.66	75,787,686.76	0.26	2,710.47
2 000 000	61,438,419.15	2,457,536.77	24,458,291.54	105,305,411.51	0.22	2,573.68
3 000 000	85,671,202.92	3,426,848.12	36,687,437.31	166,410,969.24	0.19	2,392.54

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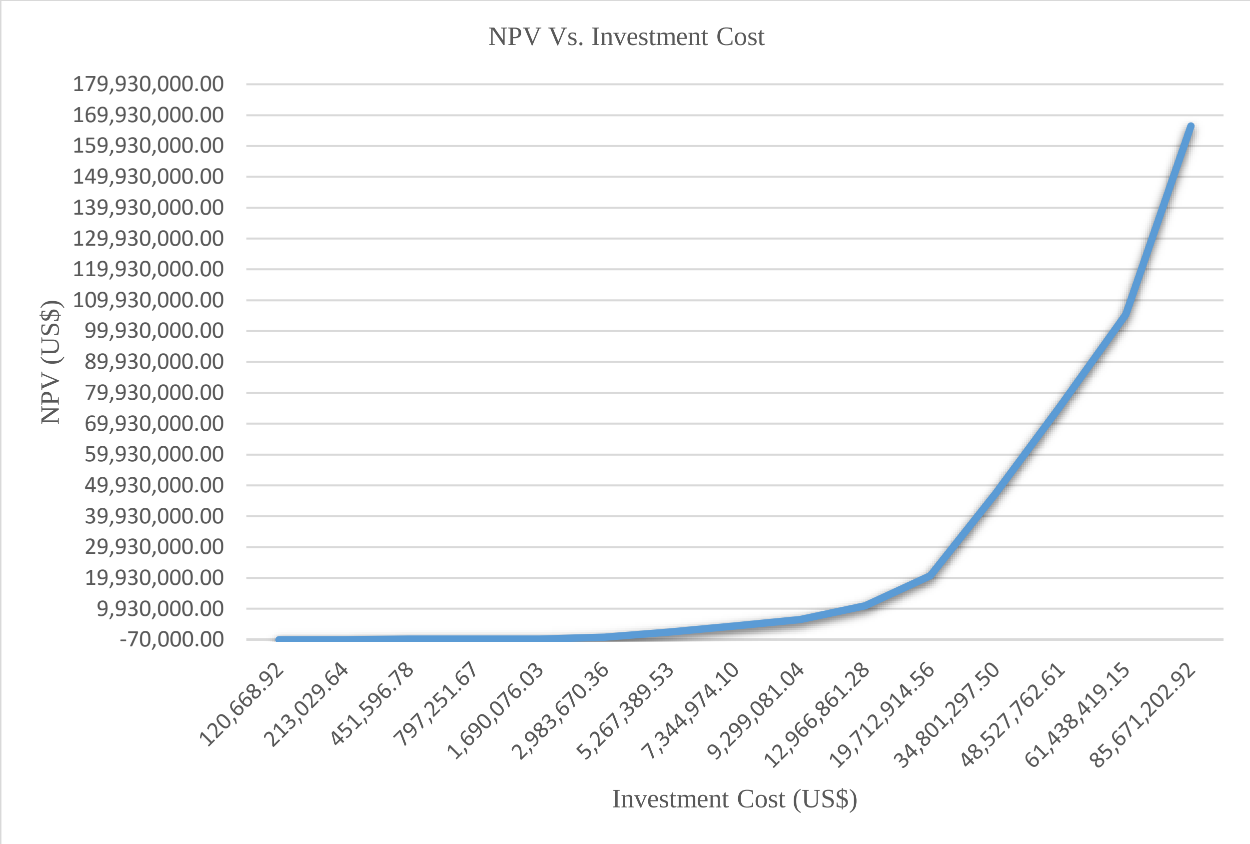

Figure 4.1 The Investment Cost of the Proposed Waste Incineration Facility Vs NPV

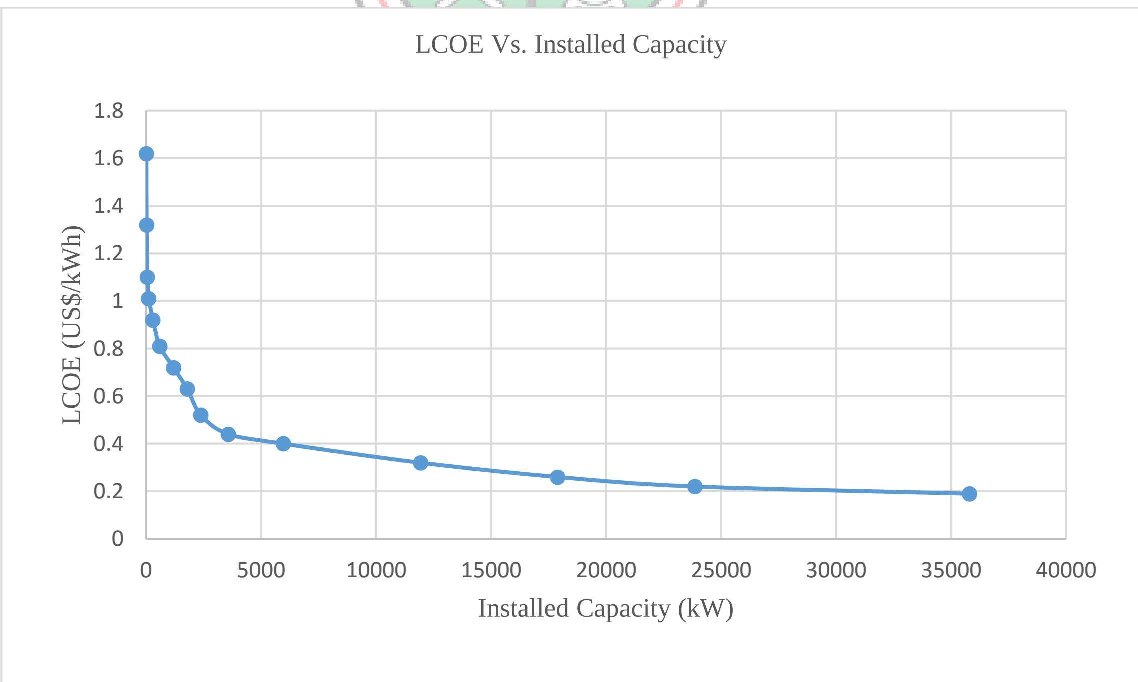

Figure 4.2 Installed Capacity of the Proposed Waste Incineration Facility Vs LCOE

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It can be observed from the table that the unit cost of electricity generated per kW in the waste incineration facility decreases with increasing installed capacity. With a population size of 5,000 inhabitants, the installed capacity was 59.68 kW and the unit cost of electricity was 7,507.04 US$/kW, with population size of 100,000 inhabitants, the installed capacity was 1 193.59 kW and the unit cost of electricity reduced to 4,413.07 US$/kW, with a population size of 500,000 inhabitants the installed capacity was 5,967.94 kW and the unit cost of electricity reduced to 3,303.13 US$/kW, and also with a population size of 3,000,000 inhabitants (which happens to be largest population size defined in the country), the installed capacity was 35,807.66 kW and the unit cost of electricity reduced further to 2,392.54 US$/kW.

It can also be observed that the NPV (with 25 years lifespan of the facility was considered in this study) increases with increasing installed capacity. With an installed capacity of 596,79 kW, the NPV was US$ 746,037.69, increasing installed capacity to 3 580.77 kW, the NPV also increased to US$ 10,907,529.09, increasing installed capacity to 17 903.83 kW, the NPV also increased to US$ 75,787,686.76, and finally increasing the installed capacity to 35 807.66 kW increases the NPV to US$ 166,410,969.24. Figure 4.1 depicts the returns on investment with respect to NPV. It can clearly be observed that the NPV improves substantially with a higher investment cost.

It can also be observed that increasing the installed capacities decreases the LCOE. With installed capacity of 2 387.18 kW the LCOE was 0.52 US$/kWh, increasing the installed capacity to 11 935.89 kW decreases the LCOE to 0.32 US$/kWh, increasing the installed capacity to 23 871.77 kW decreases the LCOE to 0.22 US$/kWh, and finally increasing the installed capacity to 35 807.66 kW decreases the LCOE to 0.19 US$/kWh.

It can clearly be observed from Figure 4.2 that increasing the installed capacity of the facility reduces the LCOE. Which implies that for a cheaper cost of electricity it is prudent to invest in a higher installed capacity.

4.4 Analysis on Incorporating Waste Incineration Facilities into Ghana's Energy Mix

Waste incineration with energy recovery can contribute to the electricity generation when integrated into the country's energy mix. The contribution that can be made by electricity

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generation from proposed waste incineration facilities to be installed in various localities in Ghana was therefore analysed considering three scenarios. i. Business as usual, meaning in the case where there are no incineration facilities built (that is only thermal power plants fuelled by the traditional fuel sources in the country), ii. Low deployment case, that is when there are just a few waste incineration plants built, and iii. High deployment case, that is when the maximum feasibly possible incineration plants built.

4.4.1 Business as usual

There are currently about 15 thermal power plants operating in the country generating about 3,753 MW of electricity. The total amount of CO_2 emissions from these thermal plants was determined to be 5,986,759.20 tonnes per year, however, this is considered the minimum total CO_2 emissions from the thermal power plants as explained earlier. The emissions of these greenhouse gases into the environment have grave environmental consequences. It is estimated that agriculture contributes about 54 % to Ghana's GDP, constitutes about 40 % of export earnings, provides about 90 % of the food needs of the country (United States Department of Commerce, 2022), therefore, using less carbon intensity fuels in thermal power plants or replacing electricity generation from these fossil fuel fired power plants with the waste incineration with energy recovery can be a plus for the country. Since climate change can have serious consequences on the environment and consequently on agriculture.

4.4.2 Low Deployment Case

In the low deployment of waste incineration facilities into the energy mix Ghana scenario, it was assumed that three waste incineration facility were installed in three regions. The assumption proposed that at least the three (3), 35 MW waste incineration capacities are installed in the country with one (1) in the Greater Accra region, Ashanti Region, and in the Western Regions of Ghana. The installation of this proposed waste incineration facilities is expected to cover a period of 15 to 20 years. This would mean a contribution of 105 MW of electricity into the national grid from the incineration of MSW, and energy production of 919.80 GWh/year, which could meet the electricity demand of about 2.3 million inhabitants in the country. The contribution of electricity generation from three waste incineration facilities could additionally mean an annual reduction of CO_2 emissions

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of about 179,602.78 tonnes (representing about 3 % reduction in CO_2 emissions relative to business as usual annually).

4.4.3 High Deployment Case

It was determined after performing the technical assessment on waste incineration facilities in Ghana, that, the maximum feasibly energy that can be extracted from the total solid waste generation in Ghana was approximately 400 MW, which translates to about an energy production of about 3,500 GWh/year. When this maximum feasibly energy generation from waste in Ghana is harnessed, this can meet the electricity demand of about 8.5 million inhabitants annually, as well as an annual CO_2 reduction of about 638,077.19 tonnes (representing about 11 % reduction in CO_2 emissions relative to business as usual).

4.5 Results from Simulation of Models

The results from the simulation of the various models (apart from the details of emissions from the waste incineration itself, which is presented in appendix B) are presented and discussed in this section. The results presented are that of the particulate matter separation, steam power plant for electricity generation, wet scrubbing process, and MD system.

4.5.1 Waste Incineration Model

Table 4.3 presents some key results from the simulation of the waste incineration plant model. The temperature of flue gas exiting the incinerator was 690.16 °C, the volumetric flow rate of the flue gases was determined to be 125 814 m^3/h. The mole flow rate (kmol/h) of the various constituents of the flue gas exiting the incinerator was also determined. The flow rate of the various constituents of the flue gas stream after simulation of the waste incineration plant model is also presented in table 4.3. A detailed results obtained after simulation of the waste incineration plant is presented in appendix B.

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Table 4.3 Simulation Results from the Waste Incineration Plant Model

Parameter	Value
Temperature	690.16 °C
Pressure	1.01325 bar
Mass Vapour Fraction	0.997035
Mass Solid Fraction	0.00296485

4.5.2 Steam Power Model

Table 4.4 presents some key results from the steam power plant model. The indicated power and brake power of the steam cycle was determined to be 30 902.0 kW and 29 974.94 kW, respectively. The outlet temperature and isentropic outlet temperature was determined to be 116.313 °C and 101.711 °C, respectively.

Table 4.4 Results from the Simulation of Steam Power Plant Model

Parameter	Value
Indicated Power	30 902.00 kW
Brake Power	29 974.94 kW
Outlet Temperature	116.313 °C
Isentropic outlet Temperature	101.711 °C

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The thermal efficiency of the steam power cycle was estimated to be 31 %. A comprehensive detail results for the various blocks and streams used in the steam power cycle model as simulated is presented in appendix C.

4.5.3 PM Separation

Table 4.5 presents the results from the PM separation assessment. It can be observed from the table that, when only cyclone PM separation device was incorporated, the separation efficiencies for the particle size intervals from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 25 %, 43 %, 59 %, 74 %, and 85 % respectively, with an overall separation efficiency of 69.44 %.

It can also be observed from table 4.5 that. when only the fabric filter was incorporated, the separation efficiencies for the particle size intervals from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 99.03 %, 99.31 %, 99.73 %, 100.00 % and 100.00 % respectively, and an overall separation efficiency of 99.48 %. When only the ESP was incorporated, the separation efficiencies for particle size interval from of 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 96.71 %, 99.99 %, 100.00 %, 100.00 % and 100.00 % respectively, with an overall separation efficiency of 99.54 %.

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Table 4.5 Results for the Separation Efficiencies of the various PM Separation Devices Incorporated into the Waste incinerator.

Particle Size Interval	Separation Efficiency					
	Cyclone only	Fabric Filter Only	ESP only	Cyclone and ESP	Fabric Filter and ESP	All three
0.00 – 1.25 µm	0.2496	0.9903	0.9671	0.9755	0.9823	0.9876
1.25 – 3.75 µm	0.4349	0.9931	0.9999	0.9999	0.9999	0.9999
3.75 – 7.50 µm	0.5854	0.9973	1.0000	1.0000	1.0000	1.0000
7.50 – 15.00 µm	0.7428	1.00	1.0000	1.0000	1.0000	1.0000
15.00 – 26.00 µm	0.8527	1.00	1.0000	1.0000	1.0000	1.0000
Overall Separation Efficiency	0.6944	0.9948	0.9954	0.9945	0.9941	0.9949

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It can also be observed that when cyclone and ESP was incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 97.55 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.45 %.
When fabric filter and ESP was incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 98.23 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.41 %.
When the cyclone, fabric filter and ESP were all incorporated, the separation efficiencies for the particle size interval from 0.00 – 1.25 µm, 1.25 – 3.75 µm, 3.75 – 7.50 µm, 7.50 – 15.00 µm, 15.00 – 26.00 µm, was found to be 98.76 %, 99.99 %, 100.00 %, 100.00 %, and 100.00 % respectively, with an overall separation efficiency of 99.49 %.

It is therefore evident that the fabric filter and ESP particulate matter separation devices can achieve an overall separation efficiency above 99 % for all particle sizes, which makes the two the best separation devices that should be employed in the waste incineration facilities proposed for use in Ghana. However, the fabric filter separation device is adopted for use because the operation of the fabric filter device does not necessarily consume energy relative to the ESP where electricity is required to charge the particles before separation.

The flue gas stream temperature is cooled before PM separation. A parametric analysis was therefore performed, to assess how the cooling of the flue gas stream affects the separation efficiency of the incorporated PM separation device(s). The result of the parametric analysis of the cyclone PM separation device incorporated is presented in Figure 4.3.

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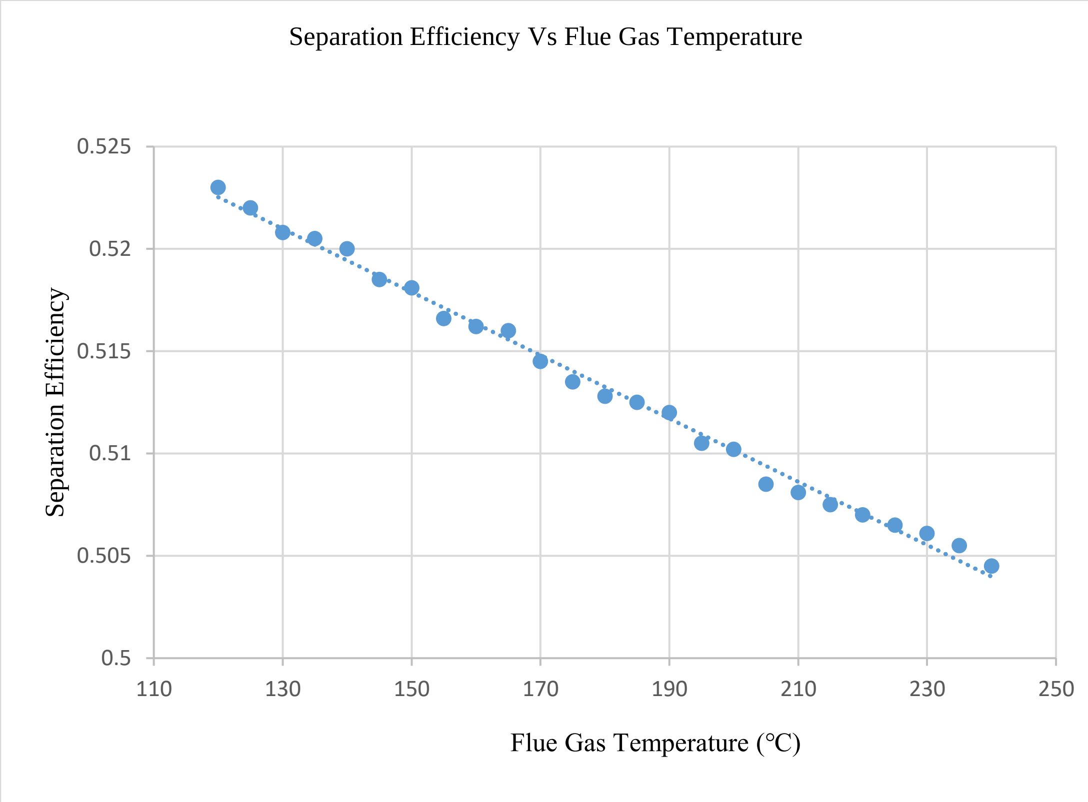

Figure 4.3. PM Separation Efficiency vs Temperature of Flue Gas for the Cyclone

It can be observed from Figure 4.3, that the separation efficiency of the cyclone PM separation device increases with decreasing temperature of the flue gas stream. This can be attributed to the fact that since the cyclone relies on centrifugal forces to separate the particles, it is able to separate larger particles, (that is when the temperature of the flue gas is cooled, the particle sizes or densities increases), however, at higher temperature of the flue gas the particles are smaller and it, therefore, reduces its separation efficiency. However, it was observed that, in the case of using fabric filter and ESP separation devices, the temperature of the flue gases that does not have a significant effect on their separation efficiencies. This can be attributed to the fact the separation efficiency in either the fabric filter or ESP does not depend heavily on the particle's size and/density. A detailed design of the three PM separation devices, and the results obtained after simulation are presented in Appendix A.

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4.5.4 Wet Scrubbing Process

Table 4.6 exhibits important findings from the wet scrubbing procedure simulation. The condensate temperature of the flue gas was 56.7 °C, a pressure of 1.01 bar. It is worth mentioning that the temperature of the flue gas condensate exceeded its dew temperature. Moreover, the temperature of the purified flue gas, which proceeds to the stack for atmospheric emission after acid gas cleaning, was 52.2 °C at a pressure of 1.01 bar, which also surpasses its dew point. Overall, the process achieved a cleaning efficiency of over 99 % for SO_2 and over 95 % for HCl. Additionally, there was a slight decrease in other components of the flue gases as they exited the wet scrubber following the cleaning process. The total liquid feed flow rate employed in the wet scrubbing amounted to 70 000 kg/h, divided into 35 000 kg/h for the first scrubber, and 35 000 kg/h for the second scrubber. It is important to note that in the second scrubber, the liquid feed comprised a mixture of water and $CaCO_3$, with a mole fraction ratio of 9:1 (water to $CaCO_3$).

Table 4.6 Simulation Results from the Wet Scrubbing Process

Parameter	**Value**
Flue Gas Condensate (Wastewater) Temp	56.7 °C
Flue Gas Condensate (Wastewater) Pressure	1.01 bar
Cleaned Gas Temperature	52.2 °C
Cleaned Gas Pressure	1.01 bar
SO_2 Cleaning Efficiency	Over 99 %
HCl Cleaning Efficiency	Over 95 %
Volumetric Flow Rate of Wastewater	19.4 m^3/h

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4.6 Parametric Studies on Thermal Energy Analysis

This section presents the results obtained from the simulation of the optimized MD model used in the study. The thermal performance of the MD system is also presented and discussed. Table 4.7 lists the results obtained after simulation of the MD model.

Table 4.7 Simulation Results from the MD System

Parameter	Value
Feed/Concentrate Outlet Temperature	77.1 °C
Coolant Stream Outlet Temperature	34.2 °C
Membrane Flux	6.22 $l/m^2/h$
Total Thermal Energy Demand	978.6 kW
Membrane Area	699 m^2
Number of Modules	303
GOR	2.34
SEC	966 kWh/m^3
TE	64.9 %

A parametric analysis to assess the effect of varying some operating parameters of the MD system was performed. The parametric analysis was performed to assess the effect of operating parameters on the thermal efficiency, gained output ratio, and specific energy consumption. These analyses were performed to determine the optimum operating parameters that MD should operate. The following sections present how this parametric analysis was carried out, the results and discussion on these analyses.

4.6.1 Thermal Efficiency

The MD system's thermal efficiency was calculated using equation 3.11 by increasing the feed inlet temperature from 75 °C to 90 °C, while keeping the coolant inlet temperature at 26 °C. The corresponding values of the determined thermal efficiency are presented in figure 4.4a. As depicted in the figure, raising the feed inlet temperature from 75 °C to 90

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°C led to an increase in TE from 50.7 % to approximately 73 %. This rise in TE can be attributed to the enhanced permeation resulting from higher feed/concentrate inlet temperatures.

Subsequently, the MD system's thermal efficiency was determined again using equation 3.11, but this time by increasing the coolant inlet temperature from 15 °C to 32 °C while maintaining the feed inlet temperature at 85 °C. The values of the determined thermal efficiency corresponding to the coolant inlet temperature are reported in figure 4.4b. It is evident from the figure that elevating the coolant inlet temperature from 15 °C to 32 °C caused a decrease in TE from 75.4 % to approximately 57 %. This decline in TE can be attributed to the reduced permeation levels resulting from the higher coolant inlet temperature. These findings align with similar studies conducted in related research (Shahu and Thombre, 2022; Elmarghany *et. al*., 2019).

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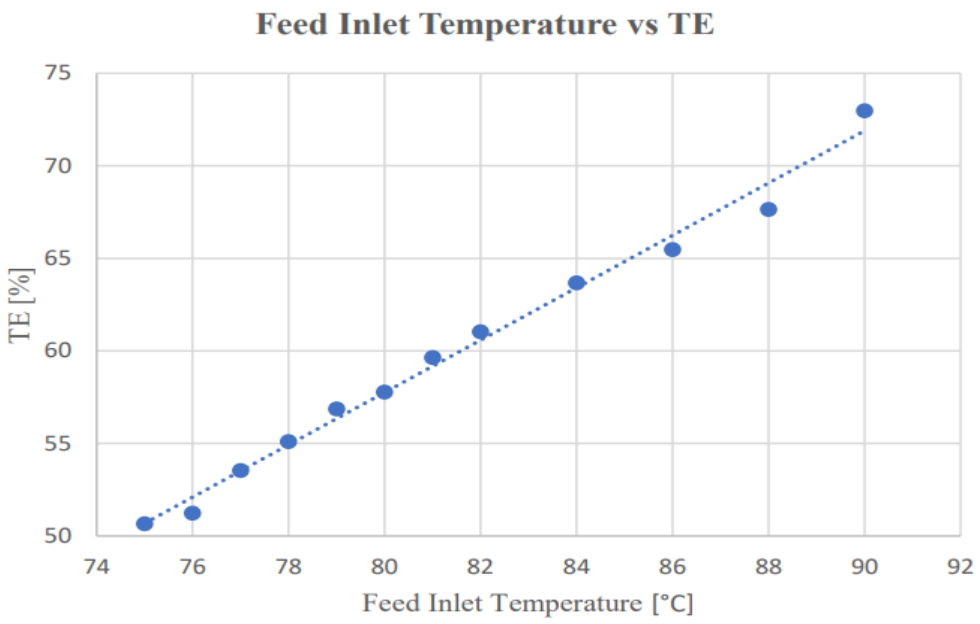

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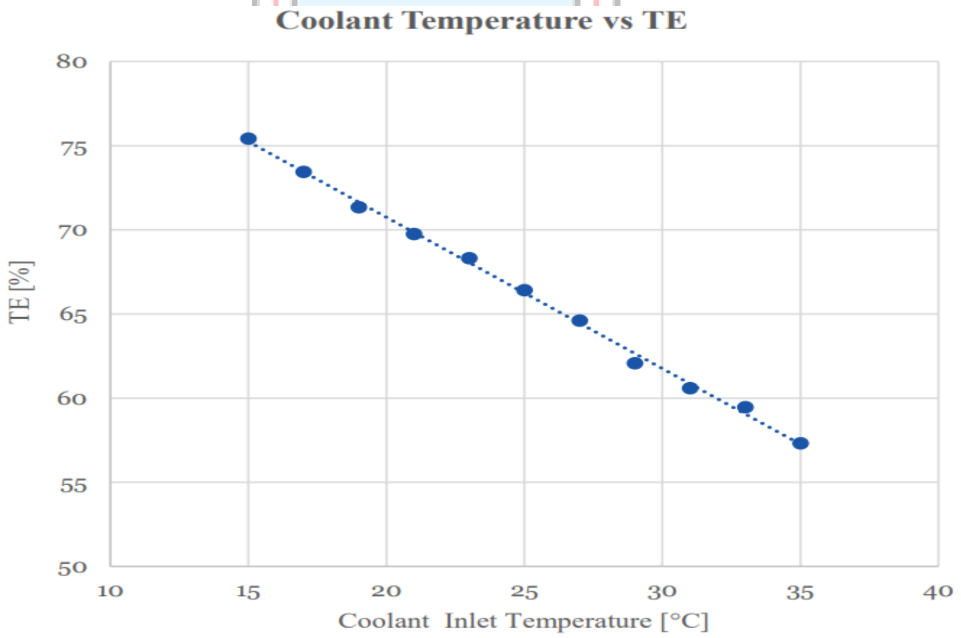

(b)

Figure 4.4 Effects on increasing Feed/Coolant Inlet Temperature versus TE (a) Effects on increasing Feed Inlet Temperature vs. TE (b) Effects on increasing Coolant Inlet temperature vs. TE.

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4.6.2 Gained Output Ratio

The Gained Output Ratio (GOR) of the MD system was determined using equation 3.14 by increasing the feed inlet temperature from 75 ℃ to 90 ℃, while keeping the coolant inlet temperature at 26 ℃. The values of the determined GOR corresponding to the feed inlet temperature are presented in Figure 4.5a. It is evident from the figure that raising the feed inlet temperature from 75 ℃ to 90 ℃ resulted in an increase in GOR from 1.82 to 2.53. This increase can be attributed to the enhanced permeation, which in turn increases the driving force of the permeate. Consequently, less thermal energy is required to produce distillate water in the MD system.

Furthermore, the GOR of the MD system was determined, but this time by increasing the coolant inlet temperature from 15 ℃ to 32 ℃, while maintaining the feed inlet temperature at 85 ℃. The values of the GOR corresponding to the inlet temperature are reported in Figure 4.4b. As depicted in the figure, increasing the coolant inlet temperature from 15 ℃ to 32 ℃ led to a decrease in GOR from 2.72 to 2.06. This decrease can be attributed to the fact increasing the coolant inlet temperature reduces the level of permeation and the driving force.

Consequently, a higher amount of thermal energy is required to produce distillate water in the MD system. These findings align with similar research conducted in the field (Shahu and Thombre, 2022; Elmarghany *et. al.*, 2019).

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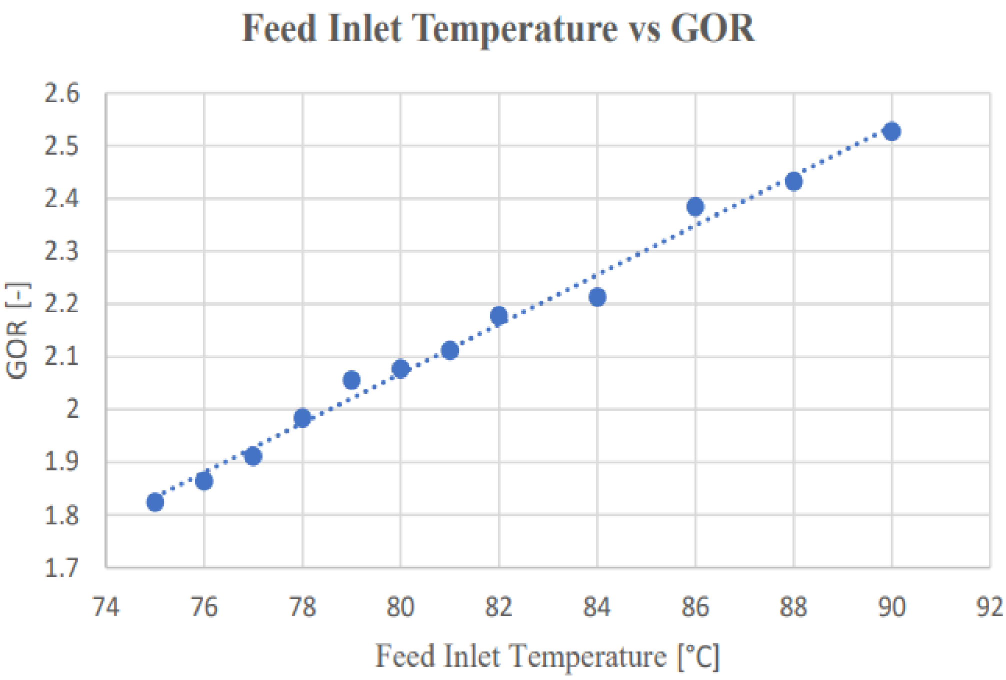

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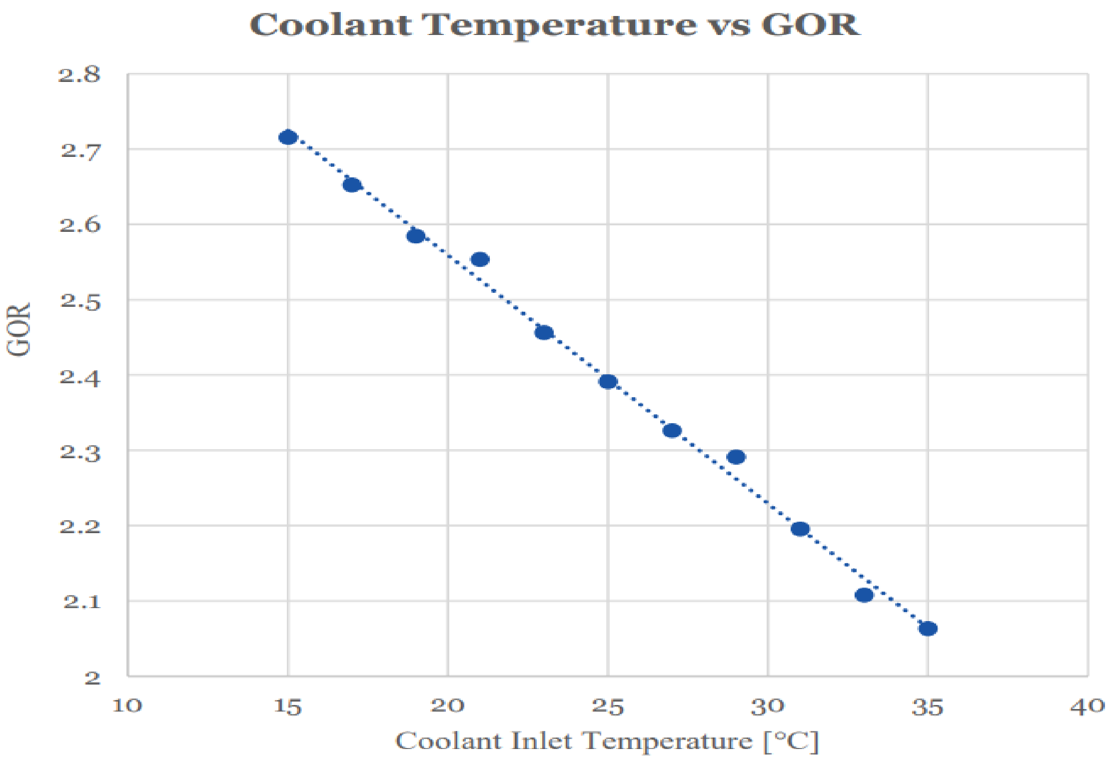

(b)

Figure 4.5 Effects on increasing Feed/Coolant Inlet Temperature versus GOR (a) Effects on increasing Feed Inlet Temperature vs. GOR (b) Effects on increasing Coolant Inlet Temperature vs. GOR.

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4.6.3 Specific Energy Consumption

The Specific Energy Consumption (SEC) of the MD system was calculated using equation 3.13, by increasing the feed inlet temperature from 75 °C to 90 °C, while maintaining the coolant inlet temperature at 26 °C. The values of the determined SEC corresponding to the feed inlet temperature are presented in Figure 4.6a. It is evident from the figure that raising the feed inlet temperature from 75 °C to 90 °C resulted in a decrease in SEC from 1237.4 kWh/m^3 to approximately 860 kWh/m^3. As mentioned earlier, increasing the feed inlet temperature enhances permeation and, consequently, increases the driving force of the permeate. This decrease in SEC can be attributed to the reduced energy required to produce distillate water due to the increase driving force.

Additionally, the SEC of the MD system was determined again using equation 3.13, but this time by increasing the coolant inlet temperature from 15 °C to 32 °C, while maintaining the feed inlet temperature at 85 °C. The values of the determined SEC corresponding to the inlet temperature are reported in Figure 4.6b. It can be observed from the figure that increasing the coolant inlet temperature from 15 °C to 32 °C resulted in an increase in SEC from 831.2 kWh/m^3 to approximately 1074 kWh/m^3. This increase in SEC can be attributed to the fact that raising the coolant inlet temperature decreases the level of permeation, which in turn reduces the driving force of the permeate. Consequently, more energy is required to produce distillate water. These findings align with similar research conducted in the field (Shahu and Thombre, 2022; Elmarghany *et. al*., 2019).

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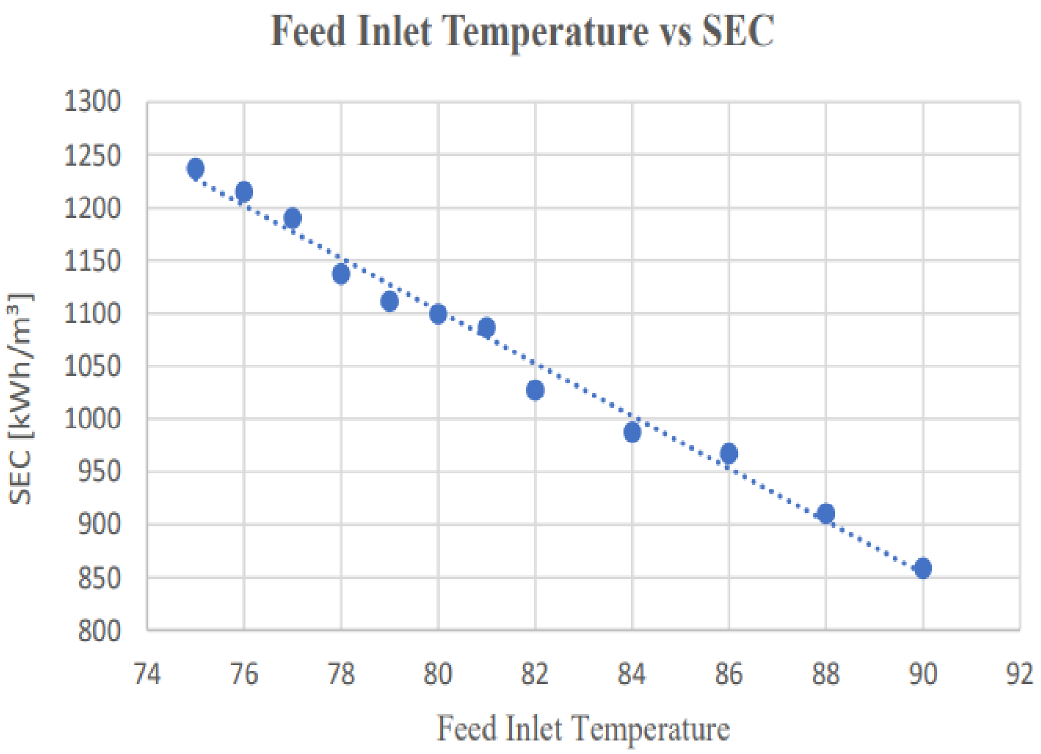

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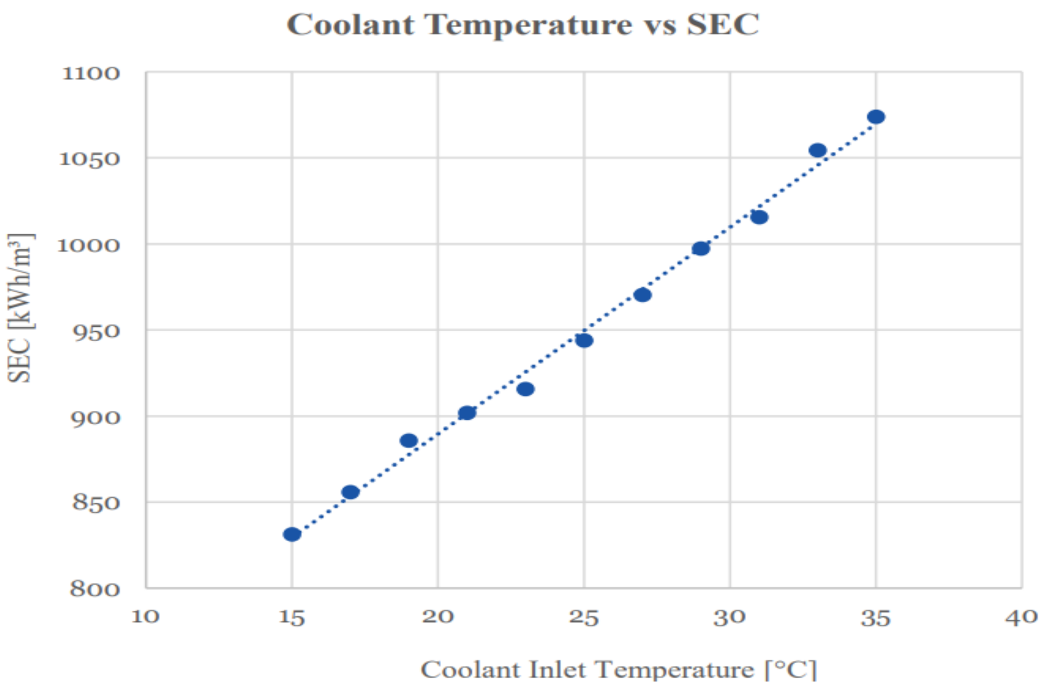

(b)

Figure 4.6 Effects on increasing Feed/Coolant Inlet temperature versus SEC (a) Effects on increasing Feed Inlet temperature vs. SEC (b) Effects on increasing Coolant Inlet temperature vs. SEC.

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4.7 Optimum WtE Choice for Use in Ghana

It can be concluded after reviewing various literature that waste incineration with energy recovery is the optimum WtE that can contribute immensely to disposal and management of MSW in Ghana. Waste incineration is a mature technology and there are currently over 2000 facilities in operation worldwide. Relative to earlier waste incineration plants which was solely meant to reduce the mass and volume of MSW, recent waste incineration plants have mechanisms which ensures that the flue gases produced during the combustion of MSW in these facilities. Although, these emission treatments may not be 100 % effective, they are at least able to treat the emissions to meet the stringent levels set by the Environmental Protection Agencies in countries where these facilities are in operation

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CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Overview

The research work proposed a waste incineration plant with energy recovery system for use in Ghana. It was found out that the waste to energy technology can contribute immensely to the disposal and management of municipal solid waste in Ghana and again to electricity generation in the country.

5.2 Conclusions

The following are the conclusions made after carrying out this research work.

i. Waste incineration with energy recovery is a matured WtE technology that can be adopted in the disposal and management of MSW in Ghana, since there are currently over 2000 of such facilities operating worldwide.

ii. A maximum total of about 400 MW of electricity can be generated from the over 14,000 tonnes of MSW generated in Ghana daily which translates into 3,504 GWh/year of energy and this can serve the electricity needs of about 8.3 million inhabitants in the country.

iii. The NPV for the installed capacity of 35 MW was positive, however, the LCOE of this installed capacity was 0.19 US$/kWh, and this is greater than the tariff of energy sales of 0.1426 US$/kWh (which is even the highest price of energy sales in the country), which means the waste incineration facility is not economically viable, waste incineration facilities would therefore need government support in terms of subsidies and tax rebates to be implemented in Ghana. It is worth mentioning that the revenues considered in this assessment was only sales from electricity generation.

iv. The simulation results of the MD process indicate that nearly complete (over 99 %) separation of the different components of the flue gas condensate can be achieved at a coolant inlet temperature of 25 °C and a feed inlet temperature of 90 °C. Earlier simulation results of the wet FGD model show that the acid gases (HCl and SO_2) in the flue gas stream cleaning, with a total volumetric flow rate of 20 m^3/h used in the process. The resulting flue gas condensate production at the end of the

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process was approximately 19.44 m^3/h. It is important to note that the energy recovered during the cooling of the flue gas stream prior to particulate matter (PM) separation is sufficient for the operation of the integrated MD system, and the wet FGD technology is an effective method for cleaning acid gases from flue gas streams, achieving separation efficiencies of 95.89 % for HCl and 99.54 % for SO_2. Additionally, the MD technology proves to be an effective method for separating these acid gases in the flue gas condensate generated by the wet FGD technology.

v. The modelling and simulation performed in this research confirms the efficacy of the PM separation devices (the fabric filter recorded an overall separation efficiency of 99.54 % for all particle sizes considered), and wet scrubbing devices in the separation of fly ashes and in acidic gas cleaning respectively, that are incorporated for the treatment of flue gases that are produced during the combustion of MSW in waste incineration facilities.

5.3 Recommendation for Future Work

The following are recommended for future work.

i. A waste incineration facility cannot be successful as a standalone venture, it should be part of an integrated waste management process, it is therefore recommended that a proper solid waste management is designed to deal with the solid waste generated in the various cities in the country.

ii. It is also recommended that proximate and ultimate analysis is performed on MSW in the various cities in the country.

iii. Three areas are recommended for the construction of the first waste incineration facilities in the country. These locations are in the Accra Metropolitan, Asokore-Mampong Metropolitan, and Takoradi-Sekondi Metropolitan Assemblies in the Greater Accra, Ashanti, and Western Regions respectively in Ghana.

iv. Although, waste incineration with energy recovery technology is the WtE technology proposed for use in the disposal and management of MSW in Ghana, there is also the need to continuously pursue the other WtE technologies (both thermochemical conversion and biological conversion methods) to augment solid

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waste disposal and management in the country, due to the diverse composition of MSW.

v. In recent times, the application of Artificial Intelligence (AI) in most sectors are being studied. In this regard, there are studies (Ihsanullah *et. al.*, 2022; Abbasi and Hanandeh, 2016) which have explored the use of this technology in the disposal and management of MSW. It is therefore recommended that the possibility of incorporating AI into the disposal and management of MSW in developing economies including Ghana are investigated.

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APPENDICES

APPENDIX A (PM Separation Device: Cyclone)

Cyclone	
Calculation options	
Model	Cyclone
Mode	**<u>Design</u>**/simulation
Calculation method	Leith-Licht
Type	stairmand-High efficiency
Design Parameters	
Separation efficiency	
Maximum Pressure drop	
Maximum number of cyclones	
Results Summary	
Diameter of cylinder (m)	0.837562
Length of vortex (m)	2.07514
Length of cylinder (m)	1.25634
Length of cone section (m)	2.09391
Diameter of overflow (m)	0.418781
Length of vortex finder (m)	0.418781
Width of gas inlet (m)	0.167512
Height of gas inlet (m)	0.418781
Diameter of underflow (m)	0.314086
Number of gas turns	7
Inlet/saltation velocity ratio	0.430697
Axial inlet gas velocity (m/s)	2.5435

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Separation Efficiencies

Particle size Interval	Efficiency
0.0 - 1.25 mu	0.249645
1.25 - 3.75 mu	0.434946
3.75 - 7.5 mu	0.58542
7.5 - 15.0 mu	0.742856
15.0 - 26.0 mu	0.85274
Overall collection efficiency	0.6944

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APPENDIX B (PM Separation: Fabric Filter)

Fabric Filter			
Calculation options		***Results Summary***	
Model	Fabric filter	Minumum Pressure drop	0.0025 bar
Mode	**Design**/Simulation	Average Pressure drop	0.0184869 bar
Filtration area calculation	calculate from estimated velocity and baghouse characteristics	Filtration time	5.44991 hr
		D50 inlet	4.6667e -06 m
		D50 solid inlet	4.18051e -06 m
Pressure drop/filtration time		D50 Vapour outlet	2.2619e -06 m
Maximum Pressure drop	0.003444 bar	Solid concentration at inlet	0.0368362 gm/l
Filter media resistance Kr	1 000 000 000/m	Solid concentration at outlet	0.000185921 gm/l
Dust resistance Coefficient	60,000	Filtration velocity	00858693 m/s
Outlet solids stream pressure	apply calculated pressure drop	Total filter area	2077.92 sqm
		Required floor area	130.034 sqm
Filter operation conditions		Number of cells	19
Filtration velocity	0.015 m/s	Number of bags per cell	78
Maximum velocity	0.0254 m/s	Number of cells cleaned	1
Minimum velocity	0.00254 m/s		
Baghouse Characteristics		***Separation Efficiency***	
Number of cleaned cells	1	Particle size Interval	Efficiency
Number of bags per cell	78	0.0 - 1.25 mu	0.990375
Filtering area per bag	1.48 sqm	1.25 - 3.75 mu	0.993125
Diameter of bag	0.154 m	3.75 - 7.5 mu	0.99725
Time required to clean bags	30 s	7.5 - 15.00 mu	1.0
		15.0 - 26.00 mu	1.0
		Overall collection efficiency	0.994775

KNOWLEDGE, TRUTH AND EXCELLENCE

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APPENDIX C (PM Separation: ESP)

ESP	
Calculation options	
Model	**Plate**/Tubular
Mode	**Design**/simulation
Calculation method	**Crawford**/Deutsch/Svarovsky
Design Parameter	
Gas velocity	2.0 m/s
Maximum height	8.4 m
Maximum width	8.4 m
Minimum length	0.1 m
Maximum length	6.3 m
Results Summary	
Gas velocity	0.773505377 m/s
Number of plates	22
Plate height	4.8178 m
Plate length	3.61335 m
Power requirement	4.33446 kW
Total width of Precipitator	4.788 m
Pressure drop	0.000197249 bar
Solid concentration of gas inlet	0.0368362 gm/l
Solid concentration of gas outlet	0.000350581 gm/l
Separation Efficiencies	
Particle size Interval	Efficiency
0.0 - 1.25 mu	0.967064
1.25 - 3.75 mu	0.999911
3.75 - 7.5 mu	1.0
7.5 - 15.0 mu	1.0
15.0 - 26.0 mu	1.0
Overall collection efficiency	0.99539

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APPENDIX D (Waste Incineration Plant)

RESULTS	
FLUE GASES	
Parameter	**Value**
Temperature	690.16°C
Pressure	1.01325 bar
mass vapour fraction	0.997035
mass solid fraction	0.00296485
FLUE GASES (COMPROD)	
Element	Mole flow (kmol/hr)
H_2O	40.0605
N_2	1095.78
O_2	206.763
NO_2	0.00240644
NO	0.0932116
S	3.03377 e-07
SO_2	0.42261
SO_3	0.119391
H_2	8.63057 e -08
Cl_2	2.67959 e -06
HCl	0.037705
CO	1.51137 e -07
CO_2	74.6885
Volume Flow Rate of Flue Gases	125 814 cum/hr

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APPENDIX E (Steam Power Plant)

RESULTS					
Description	**Units**	**HPSTEAM**	**HPWATER**	**LPSTEAM**	**LPWATER**
From		BOILER	PUMP	S-TURB	CONDENSE
To		S-TURB	BOILER	CONDENSE	PUMP
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN
MIXED Substream					
Phase		Vapour Phase	Liquid Phase	Vapor Phase	Liquid Phase
Temperature	°C	600	26.18047716	116.3132066	26
Pressure	Bar	40	40	1	1
S-TURB					
Indicated Power (kW)	30902.00				
Brake Power (BP)	29974.94				
Outlet Temperature (°C)	116.313				
isentropic outlet Temperature (°C)	101.711				

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APPENDIX F (First Journal Publication from Thesis)

energies

MDPI

Article

Wet Flue Gas Desulphurization (FGD) Wastewater Treatment Using Membrane Distillation

Noah Yakah [1,*], Imtisal-e- Noor [2], Andrew Martin [2,*], Anthony Simons [1] and Mahrokh Samavati [2]

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Abstract: The use of waste incineration with energy recovery is a matured waste-to-energy (WtE) technology. Waste incineration can reduce the volume and mass of municipal solid waste significantly. However, the generation of high volumes of polluting flue gases is one of the major drawbacks of this technology. Acidic gases are constituents in the flue gas stream which are deemed detrimental to the environment. The wet flue gas desulphurization (FGD) method is widely employed to clean acidic gases from flue gas streams, due to its high efficiency. A major setback of the wet FGD technology is the production of wastewater, which must be treated before reuse or release into the environment. Treating the wastewater from the wet FGD presents challenges owing to the high level of contamination of heavy metals and other constituents. Membrane distillation (MD) offers several advantages in this regard, owing to the capture of low-grade heat to drive the process. In this study the wet FGD method is adopted for use in a proposed waste incineration plant located in Ghana. Through a mass and energy flow analysis it was found that MD was well matched to treat the 20 m^3/h of wastewater generated during operation. Thermal performance of the MD system was assessed together with two parametric studies. The thermal efficiency, gained output ratio, and specific energy consumption for the optimized MD system simulated was found to be 64.9%, 2.34 and 966 kWh/m^3, respectively, with a total thermal energy demand of 978.6 kW.

Keywords: waste-to-energy; municipal solid waste; flue gas desulphurization; membrane distillation; thermal performance; thermal efficiency; gained output ratio; specific energy consumption

check for updates

Citation: Yakah, N.; Noor, I.-e.; Martin, A.; Simons, A.; Samavati, M. Wet Flue Gas Desulphurization (FGD) Wastewater Treatment Using Membrane Distillation. *Energies* 2022, *15*, 9439. https://doi.org/10.3390/en15249439

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1. Introduction

Waste-to-energy (WtE) technology has been established to be an appropriate method of dealing with municipal solid waste (MSW) worldwide [1]. Most developed countries have embraced the use of it as an attractive means of treating non-recyclable and non-reusable waste because not only it minimizes the risks and environmental concerns associated with disposing copious quantities of MSW into landfill sites, but also it allows production/recovery of useful energy (e.g., electricity). The use of MSW as fuel to generate energy can reduce the over-dependence on fossil fuels as sources of energy.

Waste incineration is the most matured and widely used WtE technology [1–3]. Waste incineration can reduce the volume of MSW by 80 to 95% and the mass by 70 to 75% [4]. The major setback with the use of this technology is the significant amount of pollutants that are produced. There are some constituents (e.g., hydrofluoric (HF), hydrochloric (HCl), and sulphur dioxide (SO_2)) in the flue gases emanating from waste incinerators which are proven to have a detrimental impact on the environment [5]. Therefore, strict limits on the amount of such constituents are set. Different technologies have been considered for removal of such emissions (e.g., wet, semi-dry, and dry scrubbing).

Absorption and adsorption are two distinct processes by which acidic gases are cleaned from flue gas streams emanating from waste incinerators. These processes are classified either as non-regenerative or regenerative. The non-regenerative technologies are further

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APPENDIX G (Second Journal Publication from Thesis)

clean technologies

MDPI

Review

Prospects of Waste Incineration for Improved Municipal Solid Waste (MSW) Management in Ghana—A Review

Noah Yakah [1,*], Mahrokh Samavati [2], Augustine Akuoko Kwarteng [1], Andrew Martin [2,*] and Anthony Simons [1]

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Abstract: The per capita municipal solid waste (MSW) generation per day in Ghana is estimated to be 0.47 kg/person/day, which translates to over 14,000 tonnes of solid waste generation daily. The disposal and management of this amount of solid waste has been challenging worldwide, and in Ghana, this is evident with the creation of unsanitary dumping sites scattered across most communities in the country, especially urban communities. The indiscriminate disposal of solid waste in Ghana is known to cause flooding, the pollution of water bodies, and the spread of diseases. The purpose of this review is to highlight the prospects of waste incineration with energy recovery as a waste-to-energy (WtE) technology which has contributed immensely to the disposal and management of MSW in nations worldwide (especially developed ones). The review indicates that waste incineration with energy recovery is a matured waste-to-energy technology in developed nations, and there are currently about 492 waste incineration plants in operation in the EU, over 77 in operation in about 25 states in the USA, and about 1900 in operation in Japan. Waste incineration with energy recovery is also gradually gaining prominence in developing nations like China, Brazil, Bangladesh, Nigeria, Indonesia, and Pakistan. The adoption of waste incineration with energy technology can reduce Ghana's overdependence on fossil fuels as primary sources of energy. It is, however, recommended that a techno-economic assessment of proposed waste incineration facilities is performed considering the MSW generated in Ghana. Additionally, it is also recommended that the possibility of incorporating the use of artificial intelligence technology into the management of MSW in Ghana be investigated.

Keywords: municipal solid waste; waste to energy; waste incineration; disposal; management; thermal power plant; fossil fuels; primary sources of energy

check for updates

Citation: Yakah, N.; Samavati, M.; Akuoko Kwarteng, A.; Martin, A.; Simons, A. Prospects of Waste Incineration for Improved Municipal Solid Waste (MSW) Management in Ghana—A Review. *Clean Technol.* **2023**, *5*, 997–1011. https://doi.org/10.3390/cleantechnol5030050

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1. Introduction

A World Bank report [1] estimated that 2.01 billion tonnes of municipal solid waste (MSW) is generated worldwide annually, and this is expected to increase to about 3.4 billion tonnes by the year 2050. The World Energy Council [2] also estimates that the urban MSW generation per capita (in kg/day) in Africa is 0.65, and this is expected to increase to 0.85 kg/day by the year 2025. The increase in MSW generation is attributed to an increase in population growth, global industrialisation, enhanced standard of living, and rapid urbanisation [3–6]. The disposal and management of such copious amounts of MSW have been challenging worldwide. In Ghana, the situation has become the nemesis of successive governments, and this is evident with open landfill sites created in most communities, especially urban communities, all over the country. A study [7] indicates that flooding in most areas in Ghana (especially in Accra, the capital city of Ghana) is as a result of the obstruction of drainage systems by MSW, which is disposed indiscriminately. The study also reported that in the year 2011 alone, flooding in Accra claimed fourteen (14)

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