UPPSALA UNIVERSITET

Modeling Waste to Energy systems in Kumasi, Ghana

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Minor Field Study 140
ISSN 1653-5634

September 2009 Uppsala

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Master thesis in Environmental and Aquatic Engineering, 2009
Examensarbete i Miljö- och Vattenteknik 30 hp, 2009
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ABSTRACT

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Functioning solid waste management is of great importance both for people's health and for environmental protection. The urban areas in Third World countries face a huge challenge in constructing operational and sustainable solid waste management systems. At the same time, these countries need more energy for development. The energy needs to be produced in a sustainable way, preferably from renewable sources which have a minimum environmental impact. One possibility is to use solid waste to generate electricity in centralized plants.

The purpose of this thesis was to compare benefits and environmental impacts between incineration, anaerobic digestion and landfill with gas collection as methods of solid waste management. All of these systems were assumed to generate electricity. To compare the different systems, a software model was created in MATLAB, Simulink. The impact categories compared in the study were emissions of carbon dioxide (CO_2) from fossil sources and methane (CH_4) expressed as CO_2 equivalents in global warming potential (GWP) and emissions of sulphur dioxide (SO_2) and nitrous oxides (NO_X) expressed as SO_2 equivalents as acidifying effect. The comparison was based on Life Cycle Assessment (LCA) and material flux analysis (MFA).

The study area was the city of Kumasi, the second largest city in Ghana with a population of more than 1.9 million citizens. The metropolitan area of Kumasi generates about 1 100 ton of solid waste per day. It is assumed that 70 % of the waste produced is collected. The rest of the solid waste is indiscriminately dumped in rivers or drainage systems or burned. Today, the collected waste is brought to the landfill in the outskirts of the city. The landfill is engineered and there are wells for gas collection, but the landfill gas is not collected at present.

The results from the modeling was that the incineration scenario generated most electricity, 191 000 MWh/year, the anaerobic digestion system generated 37 800 MWh/year and the landfill with gas collection system 24 800 MWh/year.

The incineration plant contributed most to emissions of both NO_X and SO_2. The emissions expressed in SO_2 equivalents were 315 ton/year. The modeled landfill and anaerobic digestion scenario emitted 12 and 22 ton SO_2 equivalents per year respectively.

The GWP of the landfill with gas collection scenario was 114 000 ton CO_2 equivalents per year. Modeled emissions from the incineration system were 81 000 ton CO_2 from fossil sources per year, while the anaerobic digestion scenario emitted 11 000 ton CO_2 equivalence per year.

Key words: Energy; life cycle assessment; mass flow assessment; anaerobic digestion; incineration; landfill; solid waste management; Kumasi, Ghana

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REFERAT

Modeling Waste to Energy systems in Kumasi, Ghana

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Fungerande system för hantering av sopor är av stor betydelse, både för människors hälsa och för att förhindra miljöpåverkan. I länder i tredje värden sker urbaniseringen snabbt. Dessa länder står framför en enorm utmaning för att bygga upp fungerande avfallshanteringssystem. På samma gång behövs mer energi för uppbyggnad och utveckling. Energin måste produceras på ett hållbart sätt, företrädelsevis från förnyelsebara källor som har minimal miljöpåverkan. En möjlighet skulle kunna vara att använda soporna för att generera el.

Syftet med examensarbetet var att jämföra fördelar och miljömässig påverkan mellan förbränning, rötning och deponering med insamling av deponigas som avfallshanterings-strategi. Alla system antogs generera el. För att jämföra de olika systemen byggdes en modell i MATLAB Simulink. De kategorier med miljöeffekter som jämfördes i studien var utsläpp av fossil koldioxid (CO_2) och metan (CH_4) mätt i koldioxidekvivalenter som global uppvärmningspotential (GWP) och utsläpp av kväveoxider (NO_X) och svaveldioxid (SO_2) uttryckt i svaveldioxidekvivalenter som försurande effekt. Jämförelsen baserades på livscykelanalys (LCA) och massflödesanalys (MFA).

Studien utfördes i Kumasi, den näst största staden i Ghana med mer än 1,9 miljoner invånare. Kumasi genererar ungefär 1 100 ton sopor per dag. Av denna mängd antas 70 % samlas in. Resterande mängd dumpas i floder, vattendrag, dagvattenrännor eller bränns. Idag sänds de insamlade soporna till en deponi i utkanten av staden. Deponin är konstruerad och övervakad, med rör för insamling av deponigas, men gasen samlas under dagsläget inte in.

Resultatet från modelleringen var att förbränningsanläggningen genererar mest el, 191 000 MWh/år, rötningsanläggningen genererade 37 800 MWh/år medan deponi med gasinsamling genererade 24 800 MWh/år.

Scenariot med en förbränningsanläggning bidrog mest med utsläpp av både NO_X och SO_2. Uttryckt i SO_2 ekvivalenter blev utsläppen 315 ton per år. Scenariot för deponin och rötningsanläggningen släppte ut 12 respektive 22 ton SO_2 ekvivalenter per år.

Alla scenarier minskade GWP jämfört med deponering av avfall utan insamling och omhändertagande av deponigas, vilket är det sophanteringssystem som används i Kumasi i nuläget.

Nyckelord: Energi, livscykelanalys, massflödesanalys, rötning, sopförbränning, deponi, avfallshantering, Kumasi, Ghana

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PREFACE

This report was written as the Master Thesis project for the degree of MSc in Environmental and Aquatic Engineering at Uppsala University. The thesis was a part of the project ”Assessing sustainability of sanitation options – Case study in Kumasi, Ghana” performed by Dr. Cecilia Sundberg at the Department of Energy and Technology, at the Swedish University of Agricultural Sciences (SLU) in Uppsala. Dr. Sundberg´s project was done in collaboration with the International Water Management Institute (IWMI) in Ghana, and the Kwame Nkruma University of Science and Technology (KNUST) in Kumasi. The project aims to evaluate different scenarios for sanitation in Kumasi in the future. The project is financed by Formas and Sida/Sarec. My part of the project was to evaluate the energy potential of the waste produced in the city of Kumasi. The fieldwork for this MSc thesis was funded by the Swedish International Development cooperation Agency (Sida) as the project was done as a Minor Field Study (MFS).

I would like to thank my supervisor; Dr. Cecilia Sundberg for good ideas, inspiration and creative solutions, but also for allowing me to take the responsibility to set the boundaries and make my own decisions.

Thanks also to my proof reader Dr. Alfredo De Toro at the Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), examiner professor Allan Rodhe at the Department of Earth Sciences Uppsala University and to Dr. Aklaku, Dr. Mensah and Mr. Rockson at Kwame Nkrumah University of Science and Engineering (KNUST). I would also like to thank the friends I met in Ghana; Shak, Harriet, Michael, Ben, George, Kofi, Daniel, Joseph, Emmanuel, Ben, Frederick, Edwin and everyone at the IWMI office in Kumasi: Ben, Leslie, Richard, Maxwell and Agustin, I hope we will meet again.

My sincere gratitude to Steve, Cinergex Solutions Ltd, Augustina, Kumasi Metropolitan Assembly, Waste Management Department, Mispah, KNUST and Inge, Avfall Sverige for answering my questions and devoting your time.

I would also like to thank the Department of Social and Economic Geography, Uppsala University for the MFS Scholarship enabling the journey to Ghana.

Last but definitely not least I would like to thank my family and all of my friends, you are wonderful! My sister Kristina, you made my visit in Ghana unforgettable.

Uppsala, May 2009

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 UPTEC W 09 017, ISSN 1401 5765
Printed at the Department of Earth Sciences, Geotryckeriet, Uppsala University, Uppsala 2009.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Städerna i dagens utvecklingsländer växer snabbt. Ett stort problem som dessa länder står inför är uppbyggnad av system för hantering av avlopp, avfall, el och vatten. På många platser finns inga system distribution av vatten och el och eller för omhändertagande av avloppsvatten och sopor. Den snabba urbaniseringen gör ofta uppbyggnaden av infrastruktur ännu mer problematisk, eftersom hus och vägar byggs innan system för hantering av avlopp och sopor. Just hantering av sopor och avfall är ett stort problem i många delar av världen, speciellt i utvecklingsländer. Bristande sophantering leder till att sopor dumpas i vattendrag, på gator eller bränns. Detta leder i sin tur till förorening av vatten och luft, men påverkar även människors hälsa negativt. Soporna drar ofta till sig insekter, råttor och andra djur som kan orsaka spridning av sjukdomar. Förutom lokal miljöpåverkan bildas metan vid syrefri nedbrytning av matavfall och fossil koldioxid vid eldning av sopor som innehåller fossilt kol. Både metan och koldioxid från fossila källor bidrar till global uppvärmning. Till fossila kolkällor räknas kol som har en omsättningstid, den tid det tar för koldioxiden att åter tas upp, längre än hundra år.

Tillgång och distribution av elektricitet är också ofta ett problem i dessa länder. I Ghana produceras merparten av elen från vattenkraft i Voltaregionen i den östra delen av landet. Här ligger Voltasjön, som är en av världens största konstgjorda sjöar och täcker 7 % av landets yta. Under år med liten nederbörd torkar vattenmagasinen ut och räcker inte till för att täcka landets behov av elproduktion. Detta inträffade i Ghana under åren 1997-1998, då bristen på elektricitet var stor i landet. Under år med normal nederbörd är problemet istället de långa avstånd som finns mellan produktionen i Voltaregionen och konsumtionen i andra delar av landet. Avståndet leder till överföringsproblem och strömavbrott är vanligt förekommande. I Kumasi inträffar i snitt ungefär ett till två avbrott om dagen med ett par timmars varaktighet. Avbrotten gör det svårt för industrier att etablera sig. För uppbyggnad och utveckling behövs mer elektricitet. Energin måste produceras på ett hållbart sätt, från förnyelsebara källor som har minimal miljöpåverkan.

En möjlighet skulle kunna vara att använda soporna för att generera el. Om sopor används för elproduktion överförs de från att vara en belastning för samhället till att bli en tillgång. Förutom fördelar som elproduktion medför kan detta leda till ett ökat intresse att samla in sopor, förmodligen skulle den mängd sopor som dumpas minska.

Studien utfördes i Kumasi, den näst största staden i Ghana med mer än 1,9 miljoner invånare. I Kumasi genereras ungefär 1 100 ton sopor per dag. Av denna mängd antas 70 % samlas in. Resterande mängd dumpas i floder, vattendrag, dagvattenrännor eller bränns. Idag sänds de insamlade soporna till en deponi i utkanten av staden. Deponin är konstruerad och övervakad. En konstruerad deponi innebär att det finns system för att förhindra läckage av vatten och gas från deponin. I deponin i Kumasi finns rör för insamling av deponigas, men gasen samlas inte in.

Syftet med examensarbetet var att jämföra fördelar och miljömässig påverkan mellan tre system för hantering av sopor i Kumasi. De tre metoder som jämfördes var förbränning, rötning och deponering med insamling av deponigas. Alla system antogs generera el.

Vid sopförbränning förbränns soporna under höga temperaturer och värmen som alstras används till att producera ånga som driver turbiner för elproduktion. Rökgaserna och det vatten som används i processen renas.

I en biogasreaktor sker nedbrytning av organiskt material under syrefria förhållanden av bakterier som lever i syrefria förhållanden. Vid nedbrytningen bildas gas som innehåller metan och koldioxid med små mängder av andra ämnen. Gasen kan förbrännas och användas för elproduktion. I en deponi sker samma process, men mycket långsammare, eftersom förhållanden som är viktiga för bakterietillväxt; temperatur, pH och vattenhalt inte kan styras på samma sätt i en deponi som i en biogasreaktor.

För att jämföra de olika systemen byggdes en modell i MATLAB Simulink. De kategorier med miljöeffekter som jämfördes i studien var utsläpp av fossil koldioxid (CO_2) och metan (CH_4) mätt i koldioxidekvivalenter som global uppvärmningspotential (GWP) och utsläpp av kväveoxider (NO_X) och svaveldioxid (SO_2) uttryckt i svaveldioxidekvivalenter som försurande effekt. Jämförelsen baserades på livscykelanalys (LCA) och massflödesanalys (MFA). LCA metodik innebär att man följer en produkt från produktion av beståndsdelar, transporter, användning och ibland även bortskaffande när produkten inte längre ska användas. Utsläpp och påverkan delas in i olika kategorier och inverkan i dessa kategorier summeras under produktens livstid. Massflödesanalys innebär att mängden av ett ämne som går in i ett system ska vara lika stor som summan av det som finns kvar av ämnet i systemet och det som går ut ur systemet.

Resultaten från modelleringen var att förbränningsanläggningen genererar mest el, 191 000 MWh/år, rötningsanläggningen genererade 37 800 MWh/år medan deponi med gasinsamling genererade 24 800 MWh/år.

Scenariot med en förbränningsanläggning bidrog mest med utsläpp av försurande ämnen. Uttryckt i SO_2 ekvivalenter blev utsläppen 315 ton per år. Scenariot för deponin och rötningsanläggningen släppte ut 12 respektive 22 ton SO_2 ekvivalenter per år.

Alla scenarier minskade bidraget till global uppvärmning jämfört med det system som används i Kumasi idag, deponering av avfall utan insamling och omhändertagande av deponigas.

Alla scenarier var bra alternativ i kategorin global uppvärmning jämfört med elproduktion från fossila källor som kol eller olja. Dessa fossila bränslen bidrar med 815 respektive 935 kg koldioxid per producerad MWh. Speciellt scenariot med förbränningsanläggningen minskade utsläppen av koldioxid per megawattimme. Simuleringar med modellen för förbränning visade på en besparing av 97 000 ton koldioxid jämfört med om samma mängd el producerats från olja.

För att välja framtida sophanteringssystem i Kumasi måste ytterligare kategorier utvärderas, som utsläpp till vatten, transporter och kostnad av installation och drift av de olika systemen.

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ABBREVATIONS

BOD	Biological Oxygen Demand
CDM	Clean Development Mechanism
COD	Chemical Oxygen Demand
EPA	Environmental Protection Agency, Ghana
GWP	Global Warming Potential
IVL	Swedish Environmental Research Institute
IWMI	International Water Management Institute
JTI	Swedish Institute of Agricultural and Environmental Engineering
KMA	Kumasi Metropolitan Assembly
KNUST	Kwame Nkrumah University of Science and Technology
KTH	Swedish Royal Institute of Technology
LCA	Life Cycle Assessment
LFG	Landfill Gas Collection
MDGs	Millennium Development Goals
MSW	Municipal Solid Waste
MFA	Material Flux Analysis
MWh	Mega Watt hour
ORWARE	ORganic WAste REsearch
Sida	Swedish International Development Cooperation Agency
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization
WMD	Waste Management Department
WTE	Waste to Energy

1. INTRODUCTION

The seventh Millennium Development Goal “Ensure environmental sustainability” is among other incentives set to reduce the number of people in the world who do not have access to basic sanitation by half in the year 2015. Basic sanitation refers to the lowest-cost technology that can certify safe and hygienic excreta removal and a healthy environment (WHO, 2009).

In some parts of the developing world, as in parts of Africa, solid waste management is considered a part of the sanitation issue. In countries where a functioning waste management system already exists the term sanitation involves mainly waste water and human excreta, not solid waste. The reason for the different terminology lies, at least partly, in the fact that when solid waste is not being taken care of but dumped in rivers and on other places or burnt it leads to sanitary problems. Sanitation plays a great part in the development of a country since it affects all sectors of the economy; health and wealth of people, tourism, protection of the environment and economic productivity. Insufficient sanitation affects all these areas and therefore the economic growth of a country negatively (Revised Environmental Sanitation Policy, 2007).

The purpose of waste management is to reduce the effects of the waste on environment and human health, but also to recapture resources from the waste (Zurbrugg, 2002). Waste management methods vary a lot between developed and developing countries, and also for urban and rural areas. In urban areas, it gets more urgent to manage the produced waste when societies grow and space gets more limited.

Solid waste that is being indiscriminately dumped is a source of spreading deceases, unpleasant odors and can lead to pollution of soil and water. Incinerated waste containing plastics releases carbon dioxide to the atmosphere and contributes thereby to climate change. Organic waste that is being landfilled undergoes anaerobic digestion. In this process, methane is released. Methane is a potent green house gas, contributing 21 times more to global warming than carbon dioxide (IPCC, 2000). In the urban and peri-urban areas which are growing rapidly in many developing countries, dumping of solid waste is a big problem.

Besides contribution to global warming, untreated incinerating smoke releases particles, toxic substances and heavy metals. This is in addition to other problems that are related to poor waste management, like attraction of rodents and insects. In large parts of Africa and in other developing countries around the world, there is a huge challenge to manage the large amounts of waste produced. The sanitation issue is of great importance for the environment as well as for people’s health (Zurbrugg, 2002).

Due to lack of resources and ability to plan and implement sewage systems, liquid and solid waste management and other sanitation issues are difficult to manage in developing countries, where houses often are built before sewage systems and other infrastructural necessities. Therefore there is a great need for environmentally and economically sustainable waste management systems to be implemented in these urban areas. The large amount of waste generated is not only a burden; it also brings possibilities for use in energy production.

The organic parts of solid waste contain useful and valuable nutrients and other substrates which are necessary and often limiting in terms of crop requirements. The remaining part, like combustible plastics, often has a high energy potential. Solid waste is thereby not only a problem, but a potential resource, even though there are many issues that must be solved such as transports, willingness to pay and illegal dumping.

To face the future problems in waste management, as well as securing the demand of renewable energy, it is necessary to reuse the resources of solid waste in energy production. Today, there are many technologies available which makes it possible to utilise the energy potential in solid waste. The two major incentives for finding an effective management of solid waste are consequently to avoid the negative effects of untreated waste and to utilize the resources that the waste contains.

The major alternatives for large scale waste management where energy can be reclaimed are land filling, incineration, anaerobic digestion and composting.

2. OBJECTIVE

The objective of this study is to construct a software model that can serve as a planning tool for use in the city of Kumasi, Ghana. The systems considered in this thesis are incineration, anaerobic digestion and landfill with gas collection. In treating solid waste with each of the methods considered in this thesis, energy can be reclaimed.

The aim of the project is to try to answer the following questions:

1. Which of the WTE methods anaerobic digestion with biogas production, incineration and landfill with gas collection is most appropriate in Kumasi in terms of electricity production?
2. Which of the WTE methods anaerobic digestion with biogas production, incineration and landfill with gas collection is most appropriate in Kumasi in terms of emissions of green house gases; CH_4, CO_2?
3. Which of the WTE methods anaerobic digestion with biogas production, incineration and landfill with gas collection is most appropriate in Kumasi in terms of emissions of acidification compounds in terms of SO_2 and NO_X?

3. GHANA

The country of Ghana is situated at the coast of western Africa (Figure 1). Ghana is a former British colony and the country became independent from British rule in 1957. The number of citizens was estimated to be 22 600 000 in 2007 (Revised Environmental Sanitation Policy, 2007). English is the official language in Ghana, but there are several domestic languages in Ghana, different in different parts of the country. Twi is the major domestic language; it is the language, besides English, spoken at marketplaces all over Ghana. The majority of the families in Ghana supply themselves from farming or working in the service sector (Country Review Report of the Republic of Ghana, 2005). The population in Ghana is increasing rapidly, especially in the urban areas. Because of the rapidly increasing urbanisation, the need for sustainable sanitation solutions is of great importance.

As the economic situation in the country improves and the (Gross Domestic Product) GDP per capita increases, the incentive for an organized solid waste management raises since a stronger economy often leads to an increased waste production due to a higher purchasing power. The GDP purchasing-power-parity increased by 7.2 % in 2008 (World Bank, 2009).

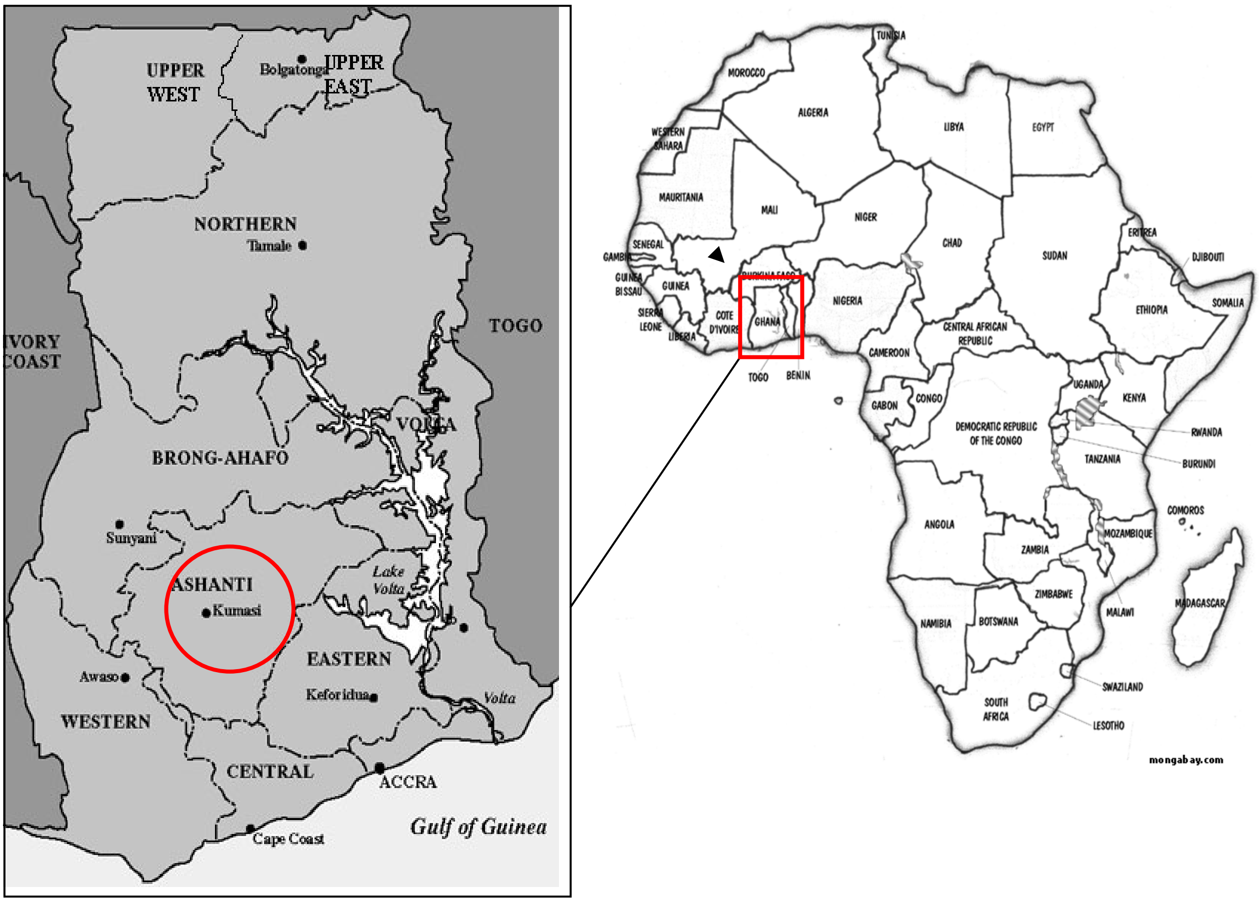

Figure 1 map of Ghana (Ghana Official Portal, 2009).

3.1. KUMASI

The Kumasi Metropolitan Area is situated in the Ashanti Region and is the second largest city in Ghana next to the capital Accra. The population growth rate in Kumasi is 5.5 % per year (Ghana Statistical Service, 2005). The city is situated in central Ghana in the forest zone about 270 km north-west of Accra. The city of Kumasi is also known as the garden city of Africa because of the many trees and green areas. Kumasi lies at an altitude of 250-350 m above sea level in the moist semi-deciduous South-East Ecological Zone. The climate is categorized as sub-equatorial, with a daily average minimum and maximum temperature in the metropolis around 21.5 °C and 30.7 °C respectively. The temperature does not vary much over the year. The average humidity is in the range of 60 % to 84 % depending on the season (KMA, 2006).

Between 1967 and 2006 the mean annual rainfall was 1350 mm (Erni, 2007). There are two rainy seasons: March to July and September to October. Many rivers are crossing the city, such as the Wiwi, Sisai, Subin, Nsuben, Oda and Owabi among others (Figure 2). These rivers are contaminated with waste in many places in the metropolis.

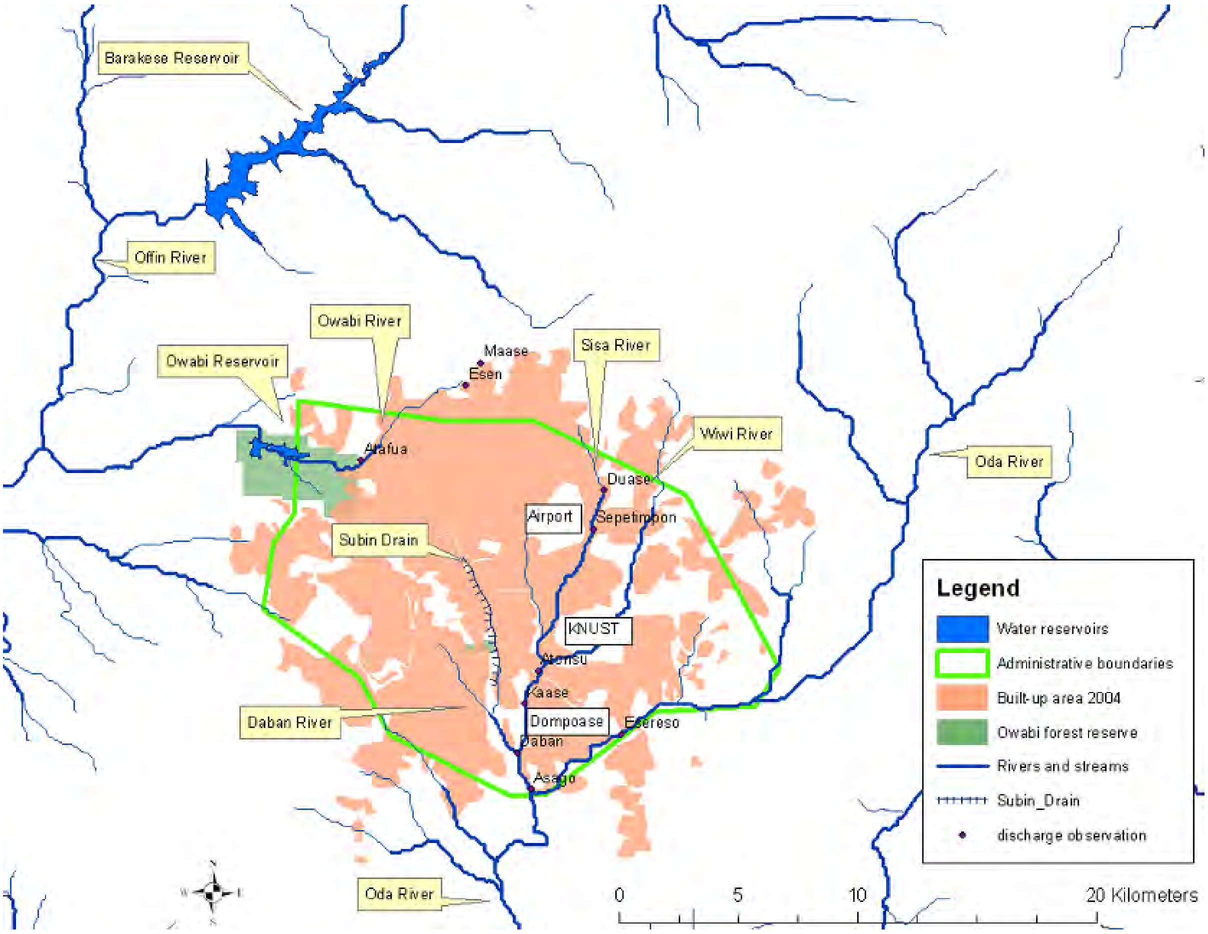

Figure 2 Map of the city of Kumasi. Rivers and the site for the landfill (Dompoase) are shown (Erni, 2007).

As Kumasi lies in the middle of Ghana it has been, and still is, a natural trading place. The market in Kumasi, Kejetia market, is one of the largest in Western Africa.

The number of citizens in Kumasi was 1 915 179 in year 2009, projected from data for the year 2000. The number of people living in Kumasi is increasing fast. The population growth rate was 5.4 % in 2008 (Acheamfuor, 2008). The fast raising of population in the city and in its outskirts moves the boundaries of the city. Kumasi covers a larger area each year since suburbs grow together with each other and with the city itself.

3.2. SOLID WASTE IN KUMASI

The waste generation per day is about 0.6 kg/person (Ketibuah et al., 2005). This gives an amount of solid waste produced in Kumasi at current date of approximately 1100 ton/day from industries, households and municipal areas. From this quantity, approximately 65-70 % of the waste generated in the city is being collected (Mensah et al., 2008).

Solid waste management is contracted to a number of private companies by the Waste Management Department in Kumasi (WMD). The collection system of the waste management in the city is based on two systems; house-to-house and communal solid waste collection (Ghanadistricts, 2008). The communal waste collection system consists of 124 containers placed throughout the city (Adjei-Boateng, pers. comm) (Figure 3). The containers are being emptied by waste collection companies in a regular basis, depending on how fast they are filled. With house-to-house waste collection, the waste is collected at the yard or door at the households. Until 2008, waste management has been subsidized by the KMA. Recently a system of Pay-as-you dump was initialized. There is also a campaign “Keep the city clean” going on in Kumasi with the aim to reduce littering and dumping of waste. The initiative involves installation of 100 public litter bins in the central districts and 80 extra communal containers to prevent overfilling the existing ones. From April 18, 2009, campaigns for cleanup of the city will start; these activities will fall together with the 10th anniversary celebrations of the King of the Kumasi area, the Ashantene (Frimpong, 2009).

Figure 3 A waste container for communal waste collection, at KNUST Kentinkrono, outside Kumasi.

The solid waste that is not being collected is being indiscriminately dumped in rivers and gutters or burned (Figure 4).

Figure 4 Waste accumulated in a drainage system in Kumasi.

Today, all of the collected solid waste in the municipality of Kumasi is transported to the landfill site at Dompoase (Figure 5). Dompoase is situated in the outskirt of Kumasi. The landfill in Kumasi is an engineered landfill. An engineered landfill is a waste disposal site where measurements have been taken to prevent environmental impact from the waste (The basics of landfill, 2003). It was started in 2003 and has an expected lifetime of 15 years (Mensah et al., 2003). It is supplied with vertical gas-outlets built as the waste amount is increasing and the landfill is growing. The gas that is being produced is not collected at present, but wells for a gas collection system are continuously installed as the landfill grows. When the landfill was constructed, the stream of the Oda River was redirected to avoid toxic and harmful substance to be flushed into the stream (Adjei-Boateng, pers. comm).

In Figure 4 one of the wells for gas collection can be seen. Pipes for landfill gas collection are continuously installed in the landfill as the waste amount is increasing. This gas collection system is not used at present but could be connected in order to collect the landfill gas generated to use it for energy purposes.

Figure 5 The landfill site in Dompoase, Kumasi.

The waste that is being landfilled in Dompoase is partly separated and recycled since human scavengers are separating useful material such as bottles and plastics to sell or use. Human scavenges are common on dumpsites all over the world (Rodic-Wiersma et al., 2008).

Some of the industries in Kumasi have their own waste water treatment plant. The Guinness Brewery has an anaerobic treatment plant and the abattoir has an aerobic plant for treatment of waste water, even though the one at the abattoir is out of function at the moment. The motive for building the treatment plant at Guinness was not for energy production, or for reuse of nutrients. The reason that the company installed the plant was to minimize the effect of the effluent on the surrounding environment. Another benefit is that the amount of waste is reduced, which leads to lower costs of waste management. The sludge from the treatment plants is brought to the landfill.

In the city of Kumasi, several research projects with environmental focus were performed in the past few years on different topics (Erni, 2007; Belevi, 2002) such as waste water irrigation, organic waste collection, food security in terms of irrigation with polluted water, health concerns and drinking water quality. There are at this time ongoing MSc theses by Mr. Joseph Marfho Boaheng and Mr. Emmanuel Adjei-Addo at Kwame Nkrumah University of Science and Technology (KNUST) focusing on willingness to pay for disposal of waste and source separation at household level. There has also been a pilot project performed in Kumasi to see the willingness to source separate waste at households in different income areas (Asase et al., 2008)

The organic waste composition from households varies depending on the season, even if the temperature and precipitation only varies a little in the Kumasi area. The average weight percent composition of household waste in Kumasi is shown in Figure 6.

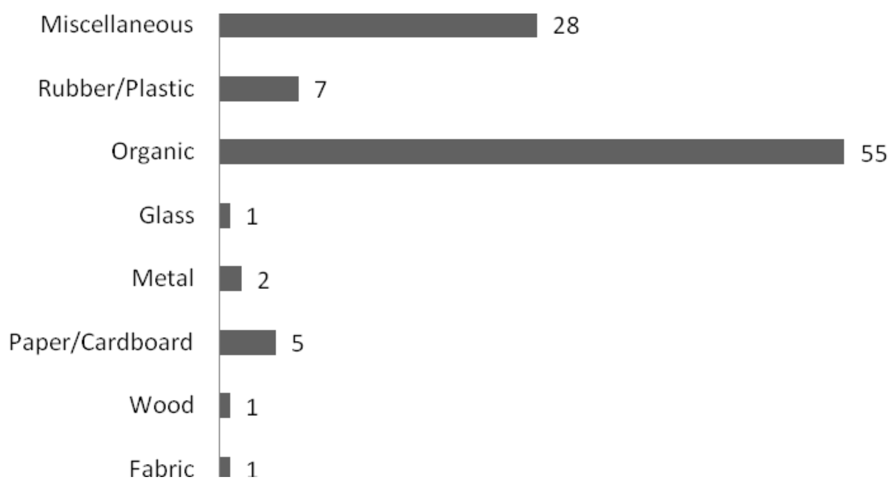

Figure 6 Percentage of each waste fraction of average household waste composition in Kumasi (Ketibuah et al., 2005).

Industrial waste from an abattoir, saw mills and a few breweries in Kumasi also add to the waste amount.

3.3. ENERGY IN GHANA

Most of the electricity in Ghana is produced and delivered from the two hydropower plants Kpong and Akosombo situated in the Volta region. The dams are situated by the lake Volta, one of the largest constructed dams in the world today. Power supply is not sufficient in Ghana. The total installed generation capacity in 2007 was 1 730 MW. In 2004 the net import of electricity to the country was 213 GWh (Reeep, 2009). In Kumasi, transmission problems often lead to failure in power supply. Another hydropower plant, Bui, is under construction (Ghana News | Projects and development, 2008). In 2006 the electricity production in Ghana was 2 810 GWh from oil and 5 619 GWh produced from hydropower and pumped storage. The total final consumption in Ghana was 6 519 GWh (IEA Energy Statistics, 2009). In 1997 and 1998 there was a severe power shortage due to the low limited rainfall. To reduce the dependency on hydropower investments are also made in thermal plants (MBendi, 2007).

In Kumasi, there are frequent power outages mainly due to transmission problems. This makes it more difficult for industries to establish in the city since the power outages interrupt production and processes (Baker, 2008). Estimations have been made that 45-47 % of the Ghanian population is connected to the grid, with access to electricity (Guide to electric power in Ghana, 2005).

There are discussions about the construction of an incineration plant for energy production from combustion of municipal solid waste from Kumasi. The plant would be built as clean development mechanism project (CDM) by Cinergex Solutions Ltd, a Canadian company (Cinergex Solutions Ltd, 2007). The site for the incineration plant would be Dompoase (Gilchrist, pers. comm).

3.4. METHODS FOR WASTE TO ENERGY PRODUCTION

3.4.1. Incineration

Municipal solid waste (MSW) incineration is performed in large scale plants where the fumes and rest products such as bottom ash are handled in order to minimize the effect on the environment. In an incineration plant the combustible fraction of the MSW are oxidized so that energy can be recovered. The chemical reaction in combustion occurs according to (Eq. 1) (Vallero, 2008).

$$(CH)_x + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

Incineration of municipal solid waste in designed incineration plants with treatment of flue gases and waste water is a system chosen more and more often both in developing and developed countries. Incineration is often a profitable system even though the installation cost is high since production of heat, steam and electricity often leads to a large economic gain.

An incineration plant in general consists of pretreatment of waste, combustion, system for flue gas purification, water treatment and management of slag and ash. Pretreatment is not always necessary, it depends on the type of incinerator since different types are more or less sensitive to the heterogeneity of the waste. Ash and slag are usually land filled (Sundqvist, 2005).

One important parameter influencing the energy potential in MSW is the heating value. The heating value is a measure of the energy which the waste contains and is determined by the chemical composition of the different fractions (Dong et al., 2003). The heating value regulates the combustion efficiency of the incinerator. It is therefore important to make sure the heating value is high enough so that no additional fuel is needed to fully combust the waste material. The lower heating value (LHV) is defined as the amount of heat produced when combusting a certain amount of fuel assuming all water is in the form of steam and is not condensed (Finet, 1987). The heating value is of great importance for the efficiency and management of the incineration plant. The minimum LHV required for the waste to combust without the addition of other fuel is 7000 kJ/kg MSW or 1.94 MWh/ton (Incineration Mauritius, 2007).

3.4.2. Anaerobic digestion

Anaerobic digestion is the process where bacteria process biomass by digesting it in an anaerobic environment. There are several types of bacteria that coexist and break down the complex organic waste in different stages. This process results in different products; one is methane, a gas that can be used for energy generation.

Carbohydrates, proteins, fats and lipids in organic matter undergo a series of biochemical conversions in anaerobic digestion. Anaerobic organisms use carbon, nitrogen, potassium and other nutrients in the organic material to build new cell protoplasm (Persson P-O, 2005). The transformation of organic material can generally be separated in two steps. The processes that occur in the first step are hydrolysis, acidification and liquefaction. The chemical compounds produced in the first step are acetate, hydrogen and carbon dioxide. In the second step, micro organisms use these substances in their metabolism, and in this process methane, carbon dioxide and also low rates of other gases are formed (Aklaku, 2008), (Figure 7).

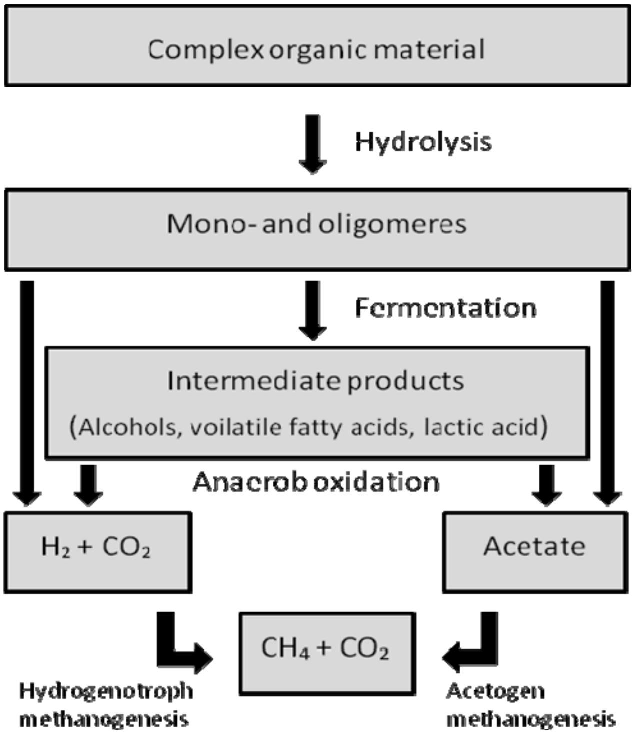

Figure 7 Processes and products in anaerobic digestion (Aklaku, 2008).

If the plant consists of one single reactor, all reactions take place at the same time. In systems with two or more reactors, the reactions take place successively in different tanks (Mata-Alvarez, 2002).

The type of anaerobic digestion is classified by the temperature in the digestion chamber. If the temperature is constant around 37 °C the digestion is preformed mainly by mesophilic bacteria. In a temperature ranging from 50-55 °C thermophilic bacteria is dominating the digestion. The amount of methane produced in the process is depending on the substrate feed to the reactor, but the methane content is usually 60-70 % (STEM, 2008).

MSW usually requires pretreatment to lower the rate of contaminants and make the organic waste homogenous. Pretreatment includes separation, chopping and mixing.

The central part of a biogas plant is the digester chamber where the organic matter has duration of stay of about 15-30 days depending on the type of system. The digestion chamber is airtight and isolated. If the digestion is operated in a cold climate, the digester is equipped with a system for heating of the feedstock (Williams, 2005). To reach thermophilic temperatures, heating is necessary regardless of climate. To make sure the organic material is not getting stratified, a blender is used. The reason for using a blender is that the yield is lower if the material inside the digester is stratified. The biogas produced is taken out in the top of the digestion chamber.

3.4.3. Landfill

Disposal of waste in landfills is the most common way to handle MSW throughout the world (Williams, 2005). A landfill is an engineered site where waste is being deposited. The landfill can either be a hole in the ground, or built on the surface of the ground. The purpose of a sanitary or engineered landfill is to dispose the waste in a way that keeps the effluent from the waste separated from the surrounding environment.

The process of degradation of organic material which can be found in a landfill is the same as the process in a biogas reactor. The difference is that biogas production from anaerobic digestion takes place in a controlled reactor and at a faster rate due to optimized conditions in the biogas reactor (Williams, 2005). Approximately 10 % of the global turn-over of carbon in nature goes through anaerobic digestion (Jönsson et al., 2006).

It is important to engineer the landfill to keep substances hazardous to the environment from leaking out (zerowasteamerica, 2007). An engineered landfill in general consists of a lining, a cover, systems of pipes for transport and collection of gas and leakage and a plant for waste water treatment. The purpose of the lining is to keep leachate from entering soil and groundwater underneath the landfill.

When choosing the site for a landfill, the geologic prerequisites are that the underlying rock is solid without cracks where leachate can reach the groundwater. It is also desirable that the geology is predictable so that if a leakage should occur, it is possible to predict where it will go. This quality makes it possible to capture the waste water before it reaches sensitive areas (The basics of landfill, 2003).

The purpose of the liner is to create a “bathtub” in the ground to keep waste water from reaching surrounding environment and groundwater beneath the landfill. Liners are categorized into three different groups: clay, plastic or composite. The leachate collection system leads the waste water produced to the water treatment plant. The water treatment usually consists of a system of ponds (The basics of landfill, 2003).

If the gas is used as fuel for cooking, for use in vehicles or for the purpose of electricity production it needs to be treated and upgraded to reduce the content of hazardous and corrosive substances and increase the content of methane (Persson, 2003).

The aim of constructing a landfill is for disposal of waste, not to utilize the energy potential in MSW. The possibility to collect landfill gas for energy purposes is only a positive opportunity since it generates energy and lowers the environmental impact of the landfill. Usually, less than 50 % of the produced gas is captured in the collection system (Williams, 2005). In this thesis land filling without gas collection is regarded a reference system since such a landfill is already in use in Kumasi.

3.4.4. Emissions from combustion

The emissions from incineration highly depend on the composition of the incoming waste, but also on the combustion efficiency of the incinerator and the technology used for flue gas treatment Depending on the fuel composition and operational circumstances nitrogen oxides, sulphur dioxide, carbon monoxide, hydrogen chloride, dioxins and furans, hydrogen fluoride, volatile organic carbon and heavy metals are emitted (Williams, 2005).

The United States Environmental Protection Agency (U.S. EPA) emission standards for acid gases from incineration are shown in Table 1.

Table 1 U.S. EPA emission standards for NO_X and SO_2 from solid waste combustion (EPA Clean Air Act)

Air emission	Emission standards	Problem
SO_2	50 % reduction	Acidification, effects on human health and corrosion
NO_X	180 ppm	Eutrophication, acidification and formation of oxidants

The biogas produced in landfills and anaerobic digesters consists primarily of methane and carbon dioxide. Usually small amounts of hydrogen sulphide and ammonia are present. Depending on the conditions in the digester or landfill and the composition of the organic matter trace amounts of hydrogen, nitrogen, carbon monoxide, halogenated or saturated carbohydrates, siloxanes and oxygen can be irregularly present in the biogas. Chlorinated dioxins, furans and phenyls can also be present in the gas (Tsiliyannis, 1999). The biogas is usually saturated with water vapor (IEA, Annual Report, 2004). When the gas is combusted SO_2 and NO_X could form from nitrogen and sulphur in the gas. It is difficult to predict the emissions from a landfill since they occur in different time scales. Even after a landfill is closed and sealed, leakage and gaseous compounds could be emitted for hundreds of years (Sundqvist, 1998).

When the biogas is combusted, methane is oxidized to carbon dioxide and water vapor. Typical concentrations of acid gases present in the combustion exhaust are shown in Table 2.

Table 2 Typical values of pollutants in exhaust from combustion of biogas with spark ignition engine (Williams, 2005 and Young & Blakey, 1990, quoted in Tsiliyannis, 1999). The concentration is given in mg per normal m^3 (Nm^3). One Nm^3 is one cubic meter of gas at 0 °C and 1 atm. pressure (Beychok, 2009)

Compound	Concentration (mg/Nm^3)
SO_2	22
NO_2	1170

3.4.4.1. CLEAN DEVELOPMENT MECHANISM, JOINT IMPLEMENTATION

On the 16th of February 2005, the Kyoto protocol was taken into force. The Kyoto protocol is an international agreement with targets for the precipitating industrialized countries to reduce their emissions of green house gases. The Kyoto protocol is linked to the United Nations Framework Convention on Climate Change (UNFCCC).

There are three mechanisms in the Kyoto Protocol, which aim to lower the emissions of greenhouse gases; emission trading, clean development mechanism (CDM) and joint implementation (JI). CDM and JI are two project based mechanisms within the frames for UNFCCC and the Kyoto Protocol. These both mechanisms make it possible for countries to invest in the construction of sustainable energy production plants in developing countries and thereby gain certifications of emissions. The investment should lead to reduction of emissions in some form, but the aim is also to transfer new technology. The projects are expected to make it easier to make industry and energy production in the country more efficient.

Countries participating in the Kyoto Protocol can, through investments in countries that are outside the protocol, gain emission quotas. CDM and JI are intended to help developing countries to develop in a more sustainable way. By committing in these projects companies and countries can gain rights of emissions since the emissions are reduced by the CDM or JI project (UNFCCC, 2008). The difference between CDM and JI is the country it is aiming at. Under the Kyoto protocol, countries are divided into two categories, Annex I and Annex II. Annex I countries are industrialized countries, while Annex II countries are developed countries. CDM projects are preformed in Annex II countries, while JI targets only Annex I countries, in aim to help the country in meeting their own targets through projects and investments. (Kyoto Protocol Summary, 2008).

3.5. ORWARE

ORWARE (Organic Waste Research) is a computer based simulation model developed for use as a tool in research of waste management systems and environmental analysis of waste management. The model can be used for calculation of environmental effects, flows of substances but also economic cost of different waste management systems.

ORWARE was developed in collaboration between KTH Industrial Environmental Protection, IVL Swedish Environmental Research Institute, JTI Swedish Institute of Agricultural and Environmental Engineering, SLU Agricultural Engineering and SLU Economics.

The ORWARE model is built in MatLab Simulink and it consists of several separate sub-models, which can be put together to represent different waste and sewage management scenarios. The scenarios are based on life cycle assessment (LCA) and material flow analysis (MFA) theory (Dalemo, 1999). The model can be used for comparing different scenarios trough simulation. The output from the model is emissions to air and water, residues and energy and the results are: emissions to air and water, energy generation. One vector is used to describe all material flows in the model. The ORWARE vector consists of 43 places for different chemical substances (Appendix 1).

In an LCA perspective, the aim is to include all the environmental aspects of a service or a product during its whole lifetime. The impact of the product is summed from extraction of raw material, use, reuse and finally disposal (Baumann et al., 2004). MFA is a tool for determining the flow of substances and builds on the balance between inflows to and outflow from a system (Sustainablescale, 2003).

4. METHOD

The first step of the project was to collect data and describe the situation in the city today. Data were collected from Kumasi regarding waste collection, waste amounts and waste content. Besides local literature sources such as KNUST libraries, Kumasi Metropolitan Assembly (KMA), Waste Management Department (WMD), Waste management companies, international literature was used as well as literature from the library of Swedish University of Agricultural Sciences (SLU) among other sources. Literature was also reviewed for technology and data on emissions in order to simulate outputs from the different scenarios.

The environmental categories evaluated were:

- GWP
- Acidification

To compare the GWP of each system, the emissions of greenhouse gases were converted to CO_2 equivalents (Table 3).

Table 3 Global warming potential of gases emitted from waste-to-energy methods (IPCC, 2000)

Species	Chemical formula	Mass (g/mol)	GWP (100 years) (kg CO_2 equivalents per kg)
Carbon dioxide	CO_2	44	1
Methane	CH_4	32.08	21
Nitrous oxide	N_2O	44.01	310

The same method was used to compare the acidifying effect of SO_2 and NO_X (Baumann & Tillman, 2004) (Table 4).

Table 4 Acidifying effects of NO_X and SO_2 emissions expressed in SO_2 equivalents (Baumann et al., 2004)

Species	Chemical formula	Mass (g/mol)	Acidifying effect
Sulphur dioxide	SO_2	64.06	1
Nitrous oxide	NO_X	46.01 (NO_2)	0.7

The slag and ash from incineration and the inorganic residue sorted out from anaerobic digestion scenario were assumed to be landfilled. The vehicles compressing and managing the waste in the landfill are assumed to be driven by diesel oil.

For the incineration scenario, it was necessary to know the LHV of the waste. Data on waste fractions in Kumasi were used. The classifications in existing data from Kumasi (Ketibuah et al., 2005) did not correspond to the classification in the method used for calculation of the LHV (Magrinho, 2008). Therefore estimations were made to divide the waste into the necessary fractions. The method of calculation of LHV was to divide the waste fractions into their chemical compositions. Based on the chemical structure of waste, the Mendeliev equation was used (Eq. 3) (Magrinho, 2008).

$$LHV_{Wet\ basis} = 4.187 * [81C + 300H - 26(O - S) - 6(9H + W)] \qquad (3)$$

where C, H, O, S and W are the amount of carbon, hydrogen, oxygen, sulphur and water in the MSW, respectively. The LHV is calculated for each fraction of waste and then added to receive total LHV.

4.1. SYSTEM BOUNDARIES

The project focused on the comparison of benefits in terms of electricity production and environmental impact in terms of global warming and acidifying gases from large scale biogas production from anaerobic digestion, incineration in waste to energy plant and landfill with gas collection.

The term energy production was used in this thesis, even though energy cannot be consumed; only transformed between different states.

Incineration, landfill and anaerobic digestion have different impacts on the surrounding environment. The focus of this project was emissions of green house gases; CH_4 and CO_2 and acidification in terms of gaseous emissions of NO_X, SO_2 of the different systems. The system boundaries were set to include onsite treatment of waste, energy production and the gaseous emissions of NO_X, SO_2, CH_4 and fossil CO_2. Emissions to water were not considered.

The three different plants were all assumed to be placed at Dompoase, the site for the landfill at present, see Figure 2 above. Due to the fact that the transport distances and emissions are the same for collection of the solid waste for all three methods, emissions from collection of waste were not included in the model (Figure 8).

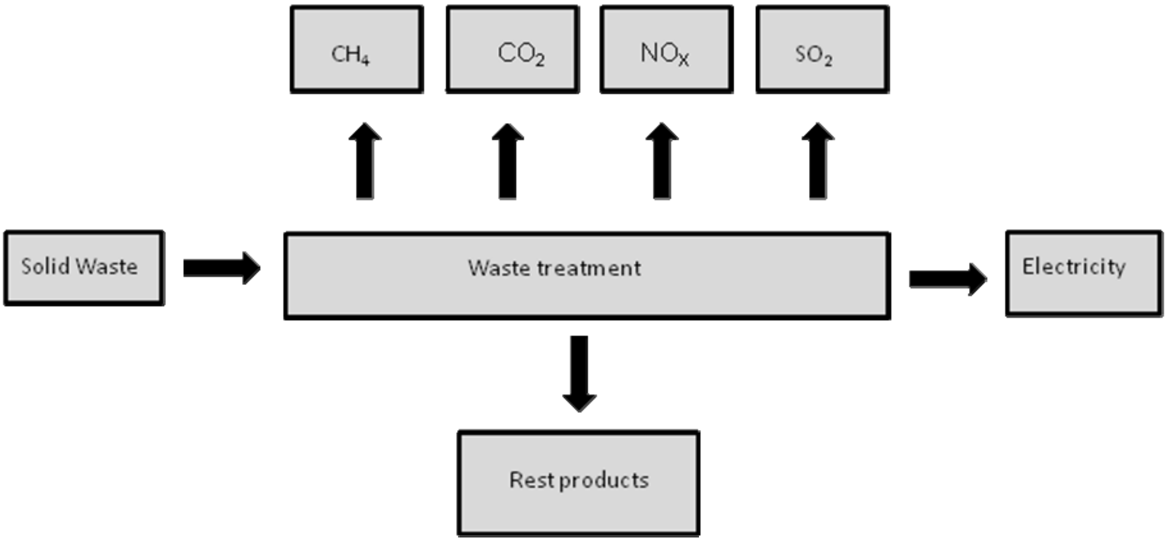

Figure 8 Chart of system boundaries.

4.1.1. The aspect of time

When comparing these scenarios, two aspects which had to be considered were the degree of disposal capacity and time during which emissions occur for each method. A landfill can manage all fractions of waste, incineration produces ash and slag which need to be taken care of and anaerobic digestion only treats the organic fraction of waste. In the model this was dealt with by calculating emissions on the potential gas production per ton of organic waste, since waste produced in one year was studied.

The waste management systems all have different time periods for both benefits and impacts on the environment. An LCA approach was used to model and evaluate the methods in terms of environmental effects. In the landfill scenario, emissions occur under a period of time reaching over hundred years, while emissions from incineration and anaerobic digestion occur almost instantaneously. To make the systems comparable, the emissions from the landfill are summed over the years they occur. The amount of waste generated in Kumasi in one year was modeled in each scenario. Both emissions and electricity production were summed from processing the waste amount from one year, regardless of the rate of degradation.

4.2. CHOICE OF TECHNICAL SYSTEMS

Based on the literature, observations and data from Kumasi a system for each treatment method was set up. The choices of the different systems were based on existing plants in developing countries and on literature.

Technical systems for each of the methods were chosen and defined. The choice in each scenario was based on different aspects: economical, need of maintenance, operation safety, efficiency in energy production and emission control. The aim of the study was not to find the optimal system, but to choose a system for each method of MSW management based on a weighing of the factors mentioned above, and to evaluate the chosen system.

4.3. MODEL CONSTRUCTION

From these systems, a software model at city level in aim to compare the technologies for future solid waste treatment in Kumasi was constructed. The model was generally built and is not site specific. If the necessary data are collected, it is possible to use it in other cities. To simplify expansion of the model to simulate other impact categories, the same vector as in the ORWARE model was used. Model calculations were executed on the ORWARE vector (Appendix 1) so that when a chemical substance changes composition, the fraction was subtracted from its place in the vector and added to the position of the substance formed in the process (Appendix 2).

The software model was based on a MFA and a LCA approach on the part of the system evaluated in this thesis. System boundaries were set starting at the point where waste enters the plant, covering eventual emissions of green house gases and acid gases emitted during pretreatment of waste, processes of combustion or degradation and energy production. All secondary products such as ash and slag from incineration and inorganic waste sorted out from anaerobic digestion were assumed to be landfilled.

The input data to the incineration submodel were the amount of waste and the chemical composition of the waste used to calculate the lower heating value. The emissions were calculated from waste compositions of the relevant compounds, formation and flue gas treatment (Figure 9).

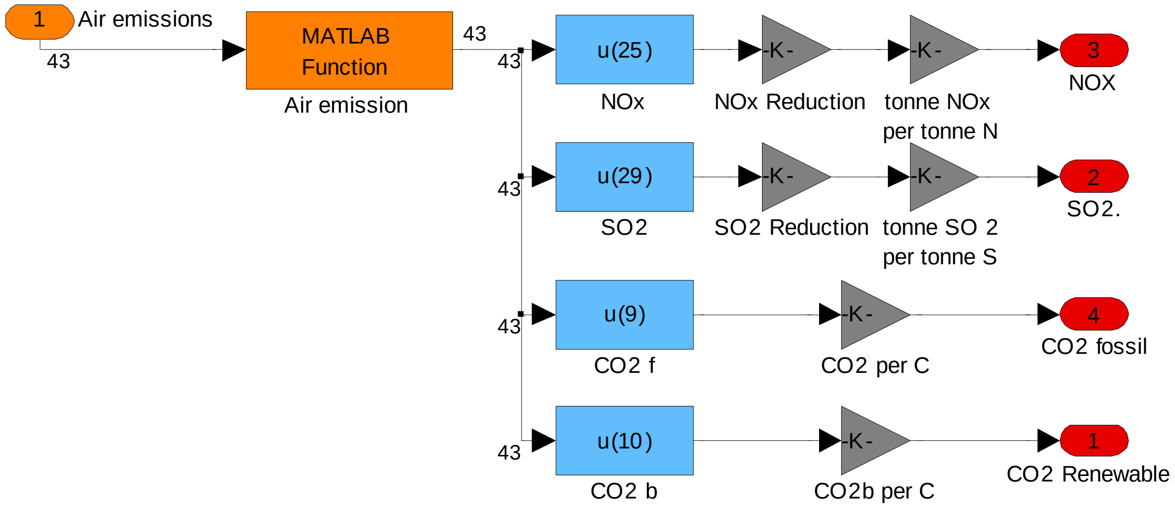

Figure 9 Air emissions submodel in incineration scenario.

Input data to the landfill and anaerobic digestion submodels were the amount of organic waste generated in Kumasi. For the calculations on gas generation and thereby electricity generation and emissions it was assumed that a fixed volume of gas was produced per ton of organic waste. The acid gas emissions were calculated from standard values in Table 2 (Section 3.4.4).

4.4. MODELING AND EVALUATION

Simulations were made with the model and the impact categories were evaluated for the different scenarios with the time for comparison of one year. GWP and acidifying effect were modeled for each scenario. The results were compared among the different systems and towards the default scenario with landfill without gas collection. Emissions from landfill management while handling these waste products were modeled and added to each scenario.

To investigate the impact of the different parameters used, sensitivity analyses were made. It was done by varying the parameters used in each scenario one by one while the other parameters were held constant to see the effect that the uncertainty of each parameter value has on the model output.

5. SYSTEM DESCRIPTION

Three technologies were studied and modeled. The scenarios were incineration, anaerobic digestion and landfill with gas collection. The following scenarios are suggestions of systems that could be suitable for Kumasi in future waste management. At present all collected waste is deposited at the landfill site in Dompoase. The suggested systems are based on literature and existing plants.

5.1. SYSTEM FOR INCINERATION

The incineration model is displayed in Appendix 6 and the MatLab calculations executed in the MATLAB Function box in the Air emissions sub model (Figure 9) is shown in Appendix 2.

The modeled incineration plant has a covered storage room where the waste is being stored. The waste generated in Kumasi is 1 100 ton per day at present. Of this amount 770 ton, 70 %, is collected and brought to the incinerator for combustion. The storage is large enough to store waste from approximately four to five days before incineration (Sundqvist, 2005).

From the storage the waste is transported to pretreatment. The purpose of the pretreatment is to separate hazardous and inert waste fractions, but also to recycle useful waste like bottles of glass. The separation of waste is partly mechanical; magnetic separator for metal, and partly manual; collection of glass, bottles and other useful things.

After the separation, the waste is weighed to make sure the incinerators are fed at a regular optimum pace. To ensure continuous drive and to avoid accumulation of waste in case of breakdown there are two incinerators. The waste is pressed with a mechanical screw, pushing fuel into a bunker where a crane is picking fuel and adding it to a feed chute which leads to the furnace (Sundqvist, 2005).

The furnace is a reciprocating grate, which is relatively insensitive to waste composition compared to other types of incinerators like fluidized beds (Amovic et al., 2009). In order to maintain sufficient oxygen level for combustion, air is taken from the waste storage and bunker and introduced from underneath the grate. The fact that the air is subtracted from the waste storage helps minimizing bad odor. The plant is designed to run for 24 hours, 365 days a year. Two weeks of maintenance is estimated necessary for reparations and overhaul per annum to assure continuous drive. The maintenance is made on one incinerator a time so that production is never completely stopped.

The combustible materials incinerate while transported on the reciprocating grate (Sundqvist, 2005). The temperature in the furnace and the duration of stay is optimized so that efficient combustion is achieved. The technology involves a combination of oxygen-deprived (gasification) and oxygen-rich (pyrolysis) treatment of the waste in a two stage system. This ensures higher temperatures and much lower emissions than would be found in older, traditional incinerators. The peak temperature can reach over 2000 °C, though there is limited practical value in going higher than 1600 °C, since dioxins or furans are not formed at such high temperatures (Gilchrist, pers. comm).

The ash and the remaining metal, glass, stones and other inert material that do not combust fall into a slag collector. The produced slag is sorted mechanically, gravel and scrap metal are recycled. The remaining ash and slag is land filled in the engineered landfill close to the incineration plant.

The flue gases from the furnace are led to an after-burn chamber where additional air, secondary air, is added (Sundqvist, 2005). This chamber is dimensioned to secure that the flue gases have an acceptable retention time and temperature to ensure complete combustion of substances. From this chamber the flue gases rise and are led into a steam boiler. In the steam boiler water is circulated through pipes and is thereby heated by the flue gases. The water is converted into high pressure steam which is used to run a turbine (Williams, 2005). The electricity needed within the plant is used and the rest is distributed to the power grid.

Due to the fact that the need of district heating is nonexistent in Kumasi and that there is no industry close to the plant that could use the heat in their processes, there is no offset for the produced heat.

The flue gas purification in the plant consists of cyclones to separate particles in the exhaust gas. A cyclone separates larger particles in the flue gas by decreasing the velocity of the gas flow, and then gravitational force will force particles to deposit. To separate finer particles, the flue gas is sent through an electrostatic precipitator. The electrostatic precipitator gives the particles in the flue gas an electrical charge as the gas passes through two electrodes. The electrodes are charged with direct current. There is usually a high voltage but a low current (Persson, 2005). After the gas has gone through the boiler it is led trough a fabric filter where SO_2 and other acid gases are removed (Amovic et al., 2009). The gas is then reheated and NO_X is removed by a selective non-catalytic reduction process (SNCR) (Johansson, pers. comm). In the SNCR method for NO_X treatment, ammonia is added to the furnace of the incinerator at temperatures between 850 and 1000 °C (Williams, 2005).

Nearly all of the sulphur combusted is forming SO_2 (Eq.4) and 10 % of the nitrogen is forming NO_X (Eq. 5) (Johansson, pers. comm).The level of flue gas treatment is assumed to be 60 % of the outgoing NO_X and 90 % of the SO_2 from the plant.

$$S + O_2 \rightarrow SO_2 \qquad (4)$$

$$N + O_X \rightarrow NO_X \qquad (5)$$

The model of the incineration plant considers emissions to air of NO_X, SO_2 and CO_2, treatment of MSW, electricity generation and disposal of slag and ash in a landfill (Figure 9).

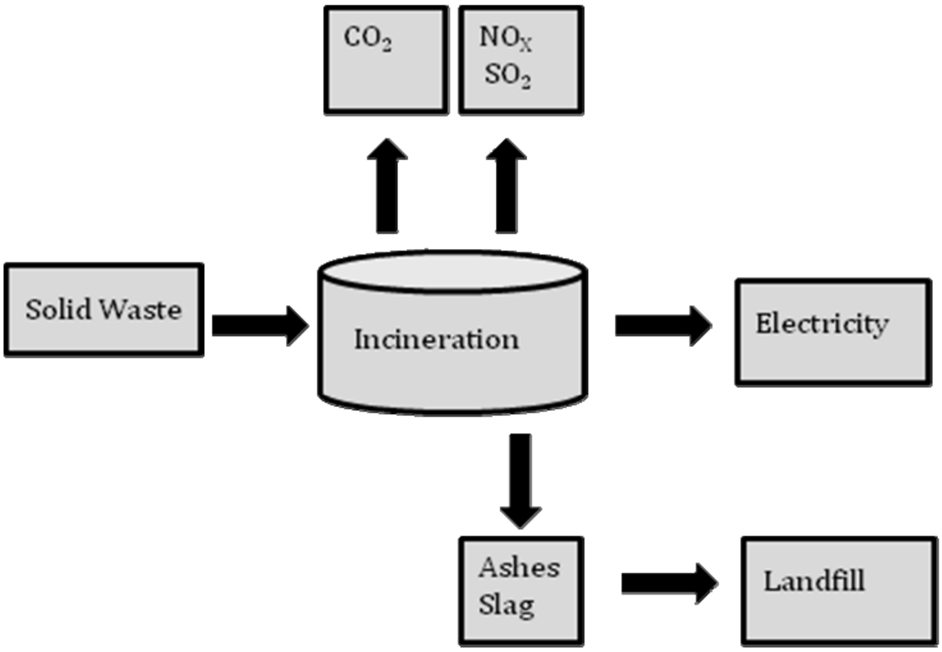

Figure 10 Processes and products considered in incineration scenario.

It is assumed that the slag and ash are reduced to 25 % of the weight of incoming waste (Combes, 2008), which gives an amount of 193 ton ash and slag per day sent to the landfill.

The LHV of the waste were calculated according to the Mendeliev equation (3) using the chemical composition data of waste fractions in Table 5 (Magrinho et al., 2008) and the amount of each fraction produced in Kumasi shown in Table 6.

Table 5 Wet chemical composition of MSW by mass (Magrinho & Semiao, 2008)

Waste part	H_20 (%)	C (%)	H (%)	O (%)	N (%)	S (%)
Food	75	11.68	2	9.72	0.53	0.03
Paper/cardboard	23	33.11	5.39	33.88	0.15	0.02
Plastic	20	48	8	18.24	0	0
Textiles	10	49.5	5.94	28.08	4.05	0.18
Wood	20	39.2	4.8	34.16	0.16	0.08
Yard	65	16.73	2.1	13.3	1.19	0.11
Rubber and leather	10	48.42	8.01	20.97	0.75	0.51
Metals	3	4.37	0.58	4.17	0.1	0
Inerts	0	0	0	0	0	0

To be able to calculate the heat value of solid waste, the different fractions of waste must be known. The fractions available for Kumasi were divided into the necessary categories used for calculation of heat value (Table 6).

Table 6 Conversions of the waste fractions from data in Kumasi translated into fractions in the model for calculation of the heat value in the waste

Waste fraction (Ketibuah et al, 2005)	%	Waste fraction (Magrinho et al, 2008)	%
Fabric	1	Textiles	1
Wood	1	Wood	1
Paper/Cardboard	5	Paper	5
Metal	2	Metal	2
Glass	1	Inert	1
Organic	55	Yard	50
		Food	5
Rubber/Plastic	7	Rubber and leather	4
		Plastic	3
Miscellaneous	28	Wood	5
		Yard	10
		Inert	5
		Plastic	8

Fabric, textile, wood, paper and metal are defined in both categorizations. Glass is not defined in the classification used to calculate the heat value (Magrinho et al., 2008) and is here classified as inert. Of the 55 % organic waste, 5 % is assumed to be food and 50 % yard waste. This assumption was made because a lot of yard waste is produced; orange, coconut and plantain shells to mention some. The amount of food waste produced is assumed to be small and also, dogs and other animals consume a lot of the food wastes. Rubber/plastic is assumed to contain 4 % of rubber from tires and leather waste from e.g. sandal production and 3 % plastic waste. In the data from Kumasi there is a large fraction of miscellaneous waste, which is assumed to be 10 % yard waste, 5 % wood, 8 % plastic and 5 % inert material like stons and sand from e.g. sweeping of floors and yards. These assumptions are based on observations in the city and on reasoning about the waste composition. The amounts of the different waste fractions according to these assumptions are shown in Figure 11.

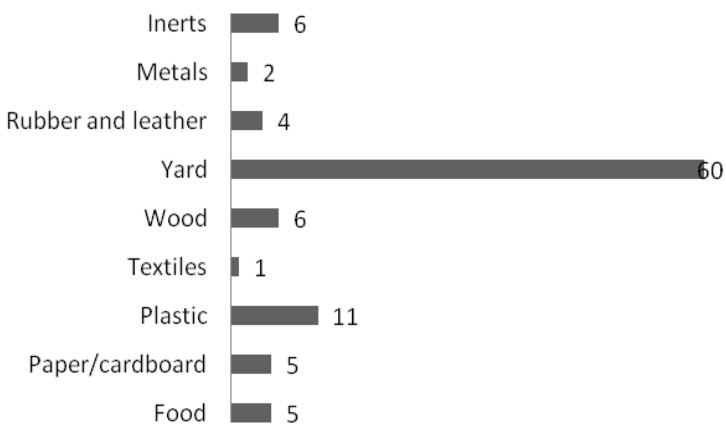

Figure 11 Percentage of each waste fraction in Kumasi for calculation of LHV.

5.1.1. Key parameters for incineration

The aim when incinerating MSW is to transfer all of the combustible material to mainly CO_2 and H_2O and to separate other substances formed in the process in flue gas cleaning equipment. If the combustion process is complete, all of the products remaining after incineration; slag, ash and gas should be free of combustible organic material (Williams, 2005).

There are four basic parameters in the combustion process (Table 7). All of these parameters affect the combustion efficiency. The temperature in the combustor is decided mainly by the heat value of the MSW and the amount of air in relation to the stoichiometric air amount. The stoichiometric or theoretical combustion is an ideal combustion where the waste is completely combusted. When the combustion process is stoichiometric the amount of air is larger than the amount required to make sure the combustion is complete. Complete combustion means all C is assumed to be CO_2, all H to be H_2O and all S is in the form of SO_2. If there are other components of these chemical compounds like C, H_2 and CO in the exhaust fume, the combustion process is incomplete (The Engineering Toolbox, 2005)

In an ordinary MSW incineration plant, the requirement is to have a temperature of > 850 °C for more than two seconds. The retention time is the time the waste stays in a certain temperature in the incinerator. Oxygen amount is also a parameter affecting the efficiency of the combustion process along with the turbulence, mixing of air in the incinerator (Sundqvist, 2005). Both of these parameters can be held on a beneficial level with fans recycling air in the plant.

Table 7 Key parameters influencing the combustion efficiency in an incineration plant (Sundqvist, 2005)

Parameter	Effect on combustion
Combustion temperature	Affects the transformation of substances.
Retention time	The time it takes for transformation differs between substances and it is therefore important that the retention time is long enough to achieve complete combustion.
Amount of oxygen	Level must be high enough to ensure complete combustion
Turbulence	Air must be circulated in the oven to make sure good combustion

5.2. SYSTEM FOR ANAEROBIC DIGESTION

Details of anaerobic digestion scenario and model are shown in appendices 7 and 8.

The system for anaerobic digestion is designed to handle 500 tons of organic municipal waste from households and industries from Kumasi per day. That is a total capacity of 219 000 tons per year. The design of the plant is based on that 1100 tons of solid waste is produced in Kumasi per day. Of these 1100 tons, 65 % is organic (Ketibuah et al, 2005). Approximately 70 % of the waste is collected (Mensah et al., 2008) (Eq. 6).

$$1100\frac{tonne}{day} * 0.70 * 0.65 = 500.5\ \frac{tonne}{day} \quad (6)$$

The inorganic part of the waste, 270 tons per day is assumed to be disposed in a landfill after the useful parts of the waste are sorted out and reused.

The scenario is based on that the waste is not being source separated or sorted before collection. Instead the organic waste is sorted manually and mechanically before entering the plant. The waste is transported to Dompoase, where it is put in a storage room with roofing to prevent water from entering the waste. In the storage room, large inorganic waste fractions are being sorted manually. Inert material such as stones, hard plastic and glass is separated. Commonly, the separation efficiency is lower than 80 %, but this is often a sufficient sorting degree (De Baere, 2006b).

The waste is then transported by feeder bands to a shredder which slices the waste before it is screened by two rotating sieves. The first sieve has a mesh of 300mm and the other one 40mm. Ferrous metal scrap is removed by a magnetic sorter. The fraction falling through the sieve less than 40mm is brought to a ballistic separator which removes stones, gravel, glass and other heavy waste (De Baere, 2006b). The inert and inorganic material is brought to the landfill.

After sorting, the organic waste is weighed in order to feed the digester at an optimum pace.
The plant is a Dranco digestion technology plant. The Dranco technology was developed by studies of the reactions occurring in a landfill. The system was developed to optimize the relatively dry environment in which degradation of organic matter occurs in landfills. By optimizing the parameters in this process the Dranco digestion technology can process a feedstock of more than 40 % total solids (TS) (De Baere, 2006b).

This method requires minimal water and produces low amounts of liquid effluents. It consists of one digester which is fed continuously with feedstock. The organic feedstock is mixed with a part of the digested residue which is recycled from the digester (De Baere, 2006b). The system recycles microorganisms, thereby initiating digestion (Williams, 2005).

The ratio of mixing is usually 1 ton of organic matter to 6-8 tons of digested matter. The mixing occurs in a chamber in the feeding pump, feeding fresh feedstock from the pretreatment and mixing it with recycled digested matter. In this step, steam is added to the feedstock in order to raise temperature to thermophilic operation. When the organic waste and the water are mixed, the slurry is fed into a closed reactor. The reactor operates in a temperature range with temperatures between 52 °C and 57 °C. Thermophilic digestion promotes an optimal degradation, sanitation of the organic material and a relatively short retention time of 15 to 21 days (IEA, 2005). The plant is operated in a thermophilic temperature in order to sanitize the digested matter. The use of a termophilic process is justified by the use of excess heat produced in the plant for heating of the feedstock. The rest of the excess heat is used to evaporate the waste water to minimize the effluent water from the plant.

The feedstock is pumped via feeding tubes to the top of the reactor. The incoming fresh feedstock flows into and mixes with the material at the upper part of the reactor (De Baere, 2006b). The tubes are dimensioned to minimize friction and thereby energy required for pumping. Steam from excess heat is used where possible in plant operation.

The incoming feedstock is transported through the reactor by gravity. It takes approximately 3-4 days for the organic material to reach the bottom of the digester. The fact that the feedstock is pumped to the top and transported by gravity eliminates the need of mixing inside the reactor. Mixing of digested material with high TS is problematic and can lead to problems and breakage of mixing device (Williams, 2005).

Inside the digester, the generated biogas rises and is taken out through the roof to gas treatment and electricity generation. The produced biogas is extracted at the top of the tank. It is assumed that 5 % of the generated gas is leaking. The system for gas treatment consists of drying, filtering compression and cooling the gas before running it through a spark ignition engine (Williams, 2005). Conversion to electricity often has an efficiency of 30-35 % (Jönsson et al., 2006). The emissions from this type of gas treatment system and engine typically are 22 mg SO_2 per Nm^3 and 1 170 mg NO_X per Nm^3 of biogas produced (Williams, 2005). The efficiency in the engines was assumed to be 33 % in electricity generation (Electrigaz, 2006).

As much of the outflow water as possible is evaporated by excess heat. The rest of the water is sent to the on-site pre-treatment which consists of a system of water treatment ponds. The ponds are co-treating the waste water along with leakage water from the landfill and fecal sludge.

The average solid retention time of the plant is 20 days. The residue sludge is taken out underneath the reactor and dewatered with screws to a water content of about 50 % by weight. The digested matter that is not recycled back to the digester is removed and composted for about two weeks prior to its use as fertilizer or soil conditioner (Williams, 2005) (Figure 12).

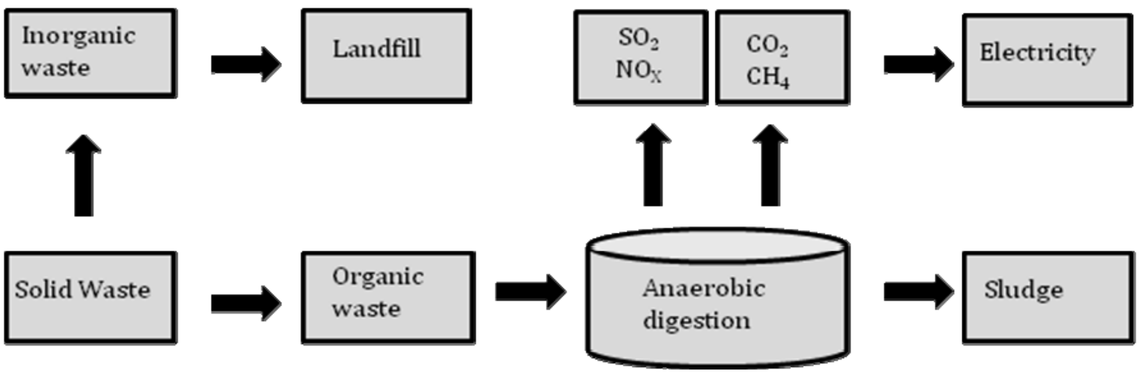

Figure 12 Flow chart of processes and products considered in the anaerobic digestion scenario.

5.2.1. Key parameters for anaerobic digestion

To have a process which is as effective as possible, it is important to make sure that the environment in the reactor is good for the microorganisms. The central parameters and the effect they have on the process are listed in Table 8.

Table 8 Process parameters, anaerobic digestion

Parameter	Effect on process
C/N Ratio	A high C/N ratio gives a high acid content and a low methane production (Williams, 2005). The optimum C/N ratio is 20-30 (SDdimensions, 1997)
Temperature	The microorganisms are sensitive to changes in temperature, methane production can be affected if the temperature varies much (Williams, 2005)
pH	6.6-8.0 gives good conditions for all types of microorganisms involved in the process. Low pH affects the methanogenic microorganisms (Williams, 2005)
Microorganisms	To start the process, microorganisms must be implemented. When the digestion is running, it is common to recycle process water to avoid that microorganisms escape from the process. It is crucial for the process that there is a satisfactory amount of microorganisms (Persson P.-O. , 2005)

Other parameters affecting the digestion and biogas production are the moisture content, retention time and organic loading rate. The concentration and type of substrate also affects the process (Hilkiah-Igoni et al., 2007).

To make sure these conditions are fulfilled in the whole reactor mixing of the substrate is very important. The agitation helps to mix fresh substrate with the bacterial population, prevents temperature gradients in the reactor, provides a uniform density of bacteria population, and prevents sedimentation and the formation of scum in the digester (Aklaku, 2008).

The gas production rate varies a lot from different sites depending on feedstock, pH, temperature and type of system. Since gas volume varies with pressure and temperature according to the general gas law (Eq. 7)

$$pV = nRT \tag{7}$$

where,

p = pressure
V = volume
n = moles of gas
R = Gas constant, depending on units used for temperature and pressure
T = temperature

The gas volume is expressed in normal cubic meters (Nm^3). One Nm^3 is the volume of one m^3 of gas at 1 atm. pressure and 0°C (Beychok, 2009). The gas generation rate can vary from 85 Nm^3/Mg MSW in European digesters; rates of 159 Nm^3/Mg have been reported in the U.S. (JG Press, 2007). Gas generation rate of around 330 Nm^3/Mg is not unusual if the conditions are good (Williams, 2005). The general amount of biogas produced from organic MSW typically varies between 100 and 200 Nm^3 biogas for each ton of MSW digested (Biogas - A renewable fuel, 2008). One Nm^3 of CH_4 weighs 0.72 kg (Levin et al., 2006). The calorific value of CH_4 is 10 kWh/Nm^3 (Svenska gasföreningen, 2009).

5.3. LANDFILL SYSTEM

Details of the landfill model and scenario are displayed in appendices 9 and 10.

The landfill scenario is based on the MSW management system existing in Kumasi today e.g. continuous use of the existing landfill, adding of a system for landfill gas collection (LFG). The waste amount being landfilled is at present approximately 281 050 ton of MSW per year.

The landfill in Kumasi has a composite liner, two layers of clay each being 150mm thick and a geomembrane. The designed depth of the landfill is 15m for a lower end and 35m for the higher end. The cover material is usually laterite, a mineral which can form layers of fine grained material (earthmuseum, 2004). Covering is performed monthly or more seldom (Asase, pers. comm).The system for gathering of leachate consists of sets of perforated underground pipes collecting the waste water that is seeping to the bottom of the landfill. The pipes direct the leachate into a system of ponds, treated along with the fecal sludge from Kumasi (Adjei-Boateng, pers. comm). In 2008, the ponds are full so the treatment is not effective (Figure 13). For more information about fecal sludge disposal and water treatment in Kumasi, see Dahlman (2009).

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Figure 13 Emptying of fecal sludge in the first pond for co-treatment of landfill leachage and fecal sludge. The landfill is seen in the background.

As the cells in the landfill are filled, wells for gas collection are installed, see Figure 3 above. In this scenario these wells were connected by a system of pipes leading the gas to a plant for gas cleaning. The collection efficiency was assumed to be 50 %. To use the gas for electricity production dehydration, removal of condensate and particulate is necessary. As the gas flows through the gas collection pipes, water vapor will condense. A system of expansion chambers is used to condense the water vapor. The system for gas treatment and electricity generation is the same as for the landfill gas scenario (Figure 14).

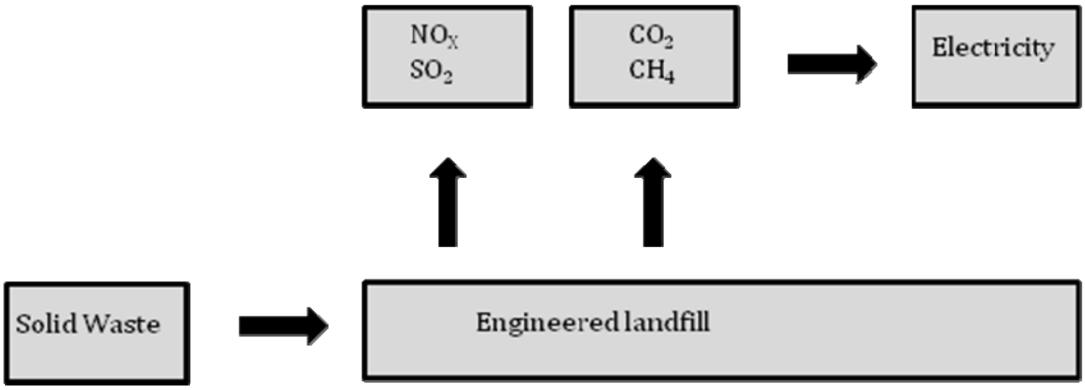

Figure 14 Processes and products considered in landfill scenario.

The waste is compressed from about 150-200 kg/m^3 to 700-800 kg/m^3 (Baumann et al., 2004) by diesel driven machines. The diesel consumption is assumed to be 40 kJ/Mg, or 0.011 MWh/Mg wastes landfilled (Sundqvist et al., 1995) in (Baumann et al., 2004). The diesel is assumed to be Diesel MK1 (Environmental Class No 1) which has an energy content of 9.780 MWh/m^3 and a density of 815 kg/m^3 (OKQ8, 2006). Emissions from diesel engines give about 3.17 ton CO_2/m^3 of diesel combusted (SMF, 2007). This gives an emission of about 0.003565 ton fossil CO_2 per ton MSW landfilled. Diesel MK1 has sulphur content lower than 10 ppm (OKQ8, 2006). The emissions of SO_2 from the landfill vehicles are therefore assumed to be negligible. The emissions of NO_X are 4.7 g/kWh (Tarberg, 2008), equaling 0.0523 g/Mg MSW landfilled.

The landfill was started in 2004 and it is estimated to last for 15 years, until 2019. The constructed phase is estimated to last 7 years, until 2011(Adjei-Boateng, pers. comm). Around the landfill area, certain kinds of tree which attract and neutralize bad odor are planted.

5.3.1. Key parameters for landfill

To obtain a secure engineered sanitary landfill, there are four crucial elements to design (Table 9).

Table 9 Main design considerations for construction of a MSW landfill

Design consideration	Function
Hydro-geologic settings	Solid layers of rock and clay resist leachage from reaching groundwater underneath the landfill
Bottom liner	The bottom liner consists of one or more impermeable layers to prevent leachate from escaping to the underlying soil and water.
Leachate collection system	Consists of pipes in the bottom of the landfill, collecting waste water and leading it to treatment.
Cover	Preventing hazardous substances from escaping through the top of the landfill.

6. RESULTS

6.1. ENERGY

The modeled electricity production was highest from the incineration scenario, 191 000 MWh/year. Simulation of the anaerobic digestion scenario gave an electricity production of 37 800 MWh/year and the landfill scenario 24 900 MWh/year (Figure 15).

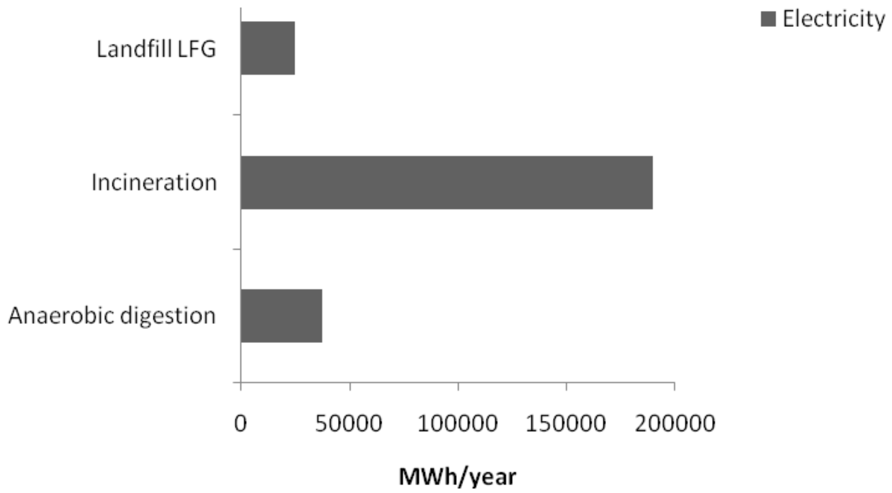

Figure 15 Electricity produced in each scenario.

The calculated LHV for MSW in Kumasi was 2.23 MWh/Mg waste (Appendix 3). The method for calculation is based on 'Estimation of residual MSW heating value as a function of waste component recycling (Magrinho et al., 2008).

According to Cinergex Solutions Ltd. previous testing suggests that the LHV in Kumasi was around 4400 BTU/lb, which equals 2.84 MWh/Mg (Gilchrist, pers. comm).

6.2. GLOBAL WARMING POTENTIAL

The modeled result of the reference scenario, landfilling without gas collection, gave a global warming potential of 228 000 tons CO_2 equivalents per year.

Of the three methods compared, the landfill system emitted most in terms of CO_2 equivalents (Figure 16). The modeled emissions of CH_4 not collected in the landfill with gas collection scenario were 5 380 tons/year. The sum of emitted CH_4 and the CO_2 emissions from diesel vehicles compacting waste in the landfill equals 114 000 tons CO_2 equivalents per year for the landfill with gas collection scenario.

The emissions from the incineration system were 81 000 tons CO_2 from fossil sources per year. These emissions came from combustion of fossil carbon in plastics in the waste.

The anaerobic scenario showed an emission of 11 000 tons CO_2 equivalents per year. These emissions came from the 511 tons CH_4 assumed leaking from the plant, 350 tons CO_2 per year come from managing the inorganic waste fractions sorted out and sent to the landfill.

The emissions from the landfill vehicles contributed an amount of 250 tons CO_2 per year for incineration system, 350 for the anaerobic digestion scenario and 1 300 tons CO_2 per year for the landfill with gas collection scenario.

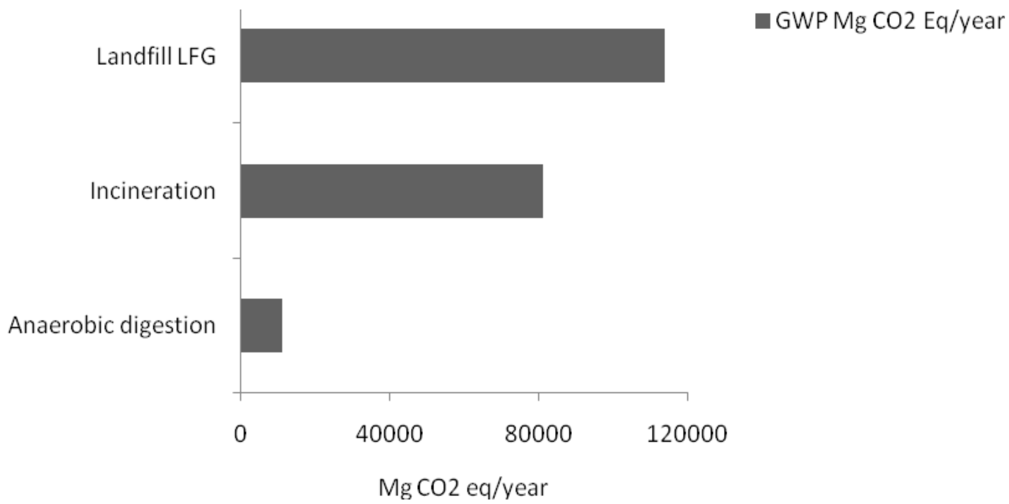

Figure 16 GWP in CO_2 equivalents from the different scenarios.

Comparison between the systems in terms of electricity generation and global warming potential per ton waste treated shows that the incineration scenario generates most electricity per ton MSW combusted and the landfill has largest impact in terms of GWP per ton municipal solid waste (Table 10).

Table 10 Electricity generation and GWP per ton MSW treated in each system

	Anaerobic digestion	Incineration	Landfill LFG
kWh electricity/ton MSW	135	680	90
GWP kg CO2 eq./ton MSW	40	290	405

The emissions from the landfill without gas collection were 228 000 ton CO_2 equivalents per year. The reduction of GWP was largest from the anaerobic digestion scenario, followed by incineration and landfill with gas collection. All of the scenarios reduced the emissions of CO_2 equivalents with more than 100 000 tons per year compared to the reference landfill scenario (Table 11).

Table 11 Reductions from each system in terms of ton CO_2 eq. per year compared to landfill without gas collection

	Anaerobic digestion	Incineration	Landfill LFG
Reduced GWP [Mg CO2 eq./year]	217 000	145 000	114 000

Calculation of GWP per MWh electricity produced shows that the anaerobic digestion scenario has the lowest GWP impact per produced unit of power (Table 12).

Table 12 Comparison of GWP and electricity production of the systems

	Anaerobic digestion	Incineration	Landfill LFG	Landfill
GWP (Mg CO2 eq./year)	11 000	81 000	114 000	228 000
Electricity (MWh/year)	37 800	191 000	24 900	-
GWP/MWh electricity	0.29	0.42	4.58	-

The landfill scenario had the highest emission of CO_2 equivalents, both per MWh of electricity generated and the total amount. The anaerobic digestion had the lowest emissions per produced MWh of electricity due to the fact that emissions are low in total from this scenario.

The incineration scenario did not emit any CH_4; the GWP came from combustion of carbon from fossil sources. The landfill and anaerobic digestion scenarios emit only CH_4 with the exception of CO_2 from landfill vehicles (Figure 17).

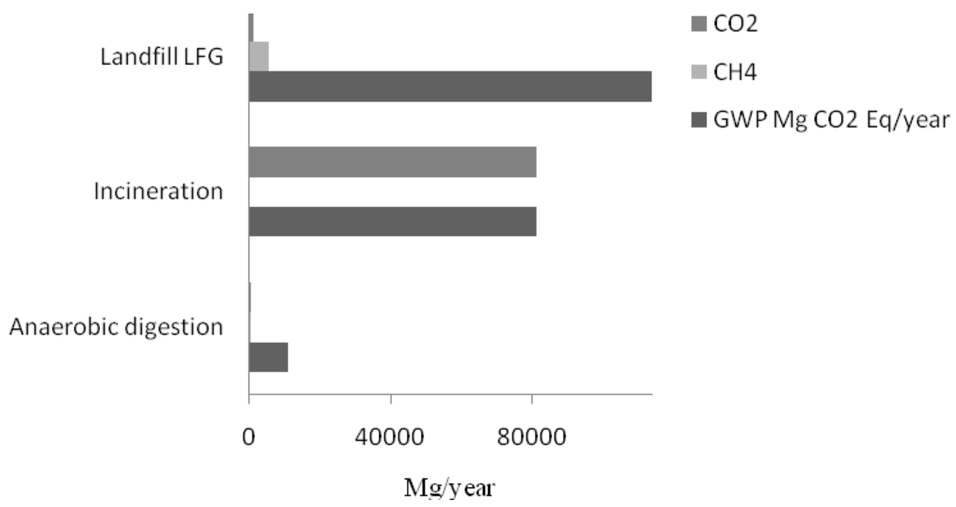

Figure 17 GWP, CH_4 and CO_2 emissions from the scenarios.

6.3. ACIDIFICATION

The emissions of both SO_2 and NO_X are highest from the incineration scenario, 102 and 304 tons per year respectively. Expressed in SO_2 equivalents the incineration scenario was emitting 315 ton SO_2 per year. The emissions from anaerobic digestion were 30 ton NO_X and 1 ton SO_2 which gave a sum of 22 ton SO_2 equivalence. Acidifying emissions were lowest in the landfill scenario (Figure 18). The modeled landfill resulted in 16 tons of NO_X; this corresponds to 12 ton SO_2 equivalents per year

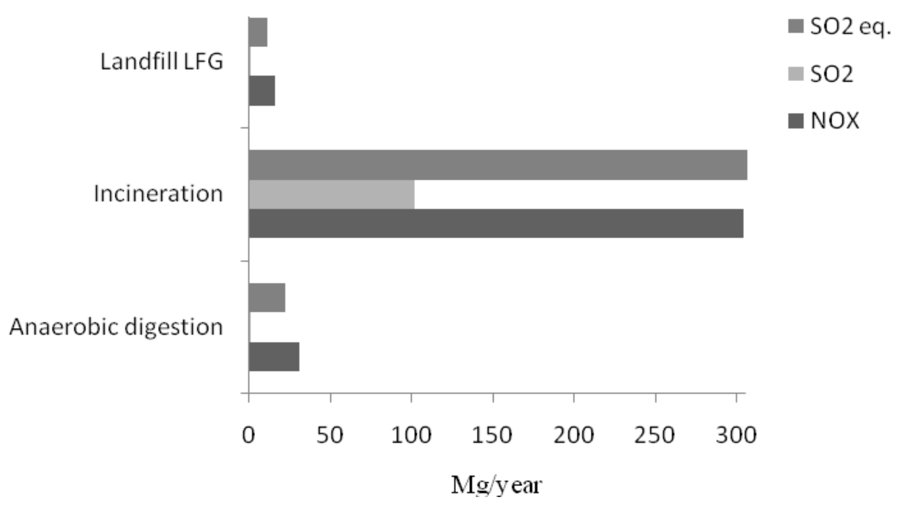

Figure 18 Acidifying effects of the different scenarios.

The landfill vehicles emitted 3.6 kg/year managing inorganic waste residual in the anaerobic digestion scenario, 2.6 kg/year managing ash and slag from incineration and 10.3 kg if all MSW disposed in the landfill (Table 13).

Table 13 Acidifying effect from each scenario, process and from residue management from landfill vehicles

	Process [Mg SO2 eq./year]	Landfill vehicles [kg SO2 eq./year]
Anaerobic digestion	22	3.6
Incineration	315	2.6
Landfill LFG	12	10.3

6.4. SENSITIVITY ANALYSIS

The aim of sensitivity analysis is to investigate the effect of input data on the output values. The input data showing large effect on the output could then be determined more precisely. The input data used in each scenario were varied one by one while the other parameters were held constant to see the effect of the uncertainty of each input data.

6.4.1. Sensitivity analysis for Incineration scenario

The names and values of input data used in the model are displayed in Appendix 5. Table 14 shows varied input data and their effect on the model output.

Table 14 Effect of process values on emissions and electricity production for incineration

Input data	Change	Electricity production	Fossil CO_2 equivalence	SO_2 equivalents
LHV	+/- 10 %	+/- 10 %	-	-
Electricity production efficiency	+/- 10 %	+/- 10 %	-	-
NOX reduction	+/- 10 %	-	-	+/- 10 %
SO2 reduction	+/- 10 %	-	-	+/- 10 %

6.4.2. Sensitivity analysis for anaerobic digestion scenario

The names and values of input data used in the model are displayed in Appendix 7. Table 15 shows varied input data and their effect on the model output.

Table 15 Effect of process values on emissions and electricity production for anaerobic digestion

Input data	Change	Electricity production	Fossil CO_2 equivalents	SO_2 equivalents
Gas production	+/- 10 %	+/-10 %	+/- 9 %	+/- 10 %
CH_4 content	+/- 10 %	+/-10 %	+/- 9 %	-
Electricity production efficiency	+/- 10 %	+/-10 %	-	-
SO_2	+/-10 %	-	-	+/- 10 %
NO_X	+/- 10 %	-	-	+/- 10 %

6.4.3. Sensitivity analysis for Landfill scenario

The names and values of input data used in the model are displayed in Appendix 9. Table 16 shows varied input data and their effect on the model output.

Table 16 Effect of process values on emissions and electricity production for landfilling

Input data	Change	Electricity production	Fossil CO_2 equivalents	SO_2 equivalents
Gas production	+/- 10 %	+/-10 %	+/-10 %	+/- 10 %
CH_4 content	+/- 10 %	+/-10 %	+/- 10 %	-
Electricity production efficiency	+/- 10 %	+/-10 %	-	-
SO_2	+/- 10 %	-	-	+/- 10 %
NO_X	+/- 10 %	-	-	+/- 10 %

7. DISCUSSION

7.1. ENERGY

Heat from electricity production is of no use in Kumasi at present. If there would have been industries close to Dompoase with need of heat or steam, the profit and efficiency would increase since the heat production is between 60 and 70 % of the total energy produced in all plants (Figure 19). In the anaerobic digestion scenario, the heat is used to maintain the termophilic operation and to evaporate the process water.

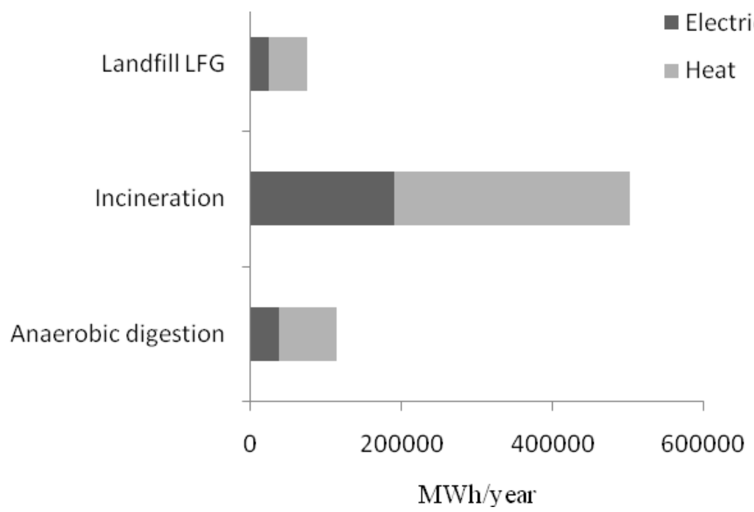

Figure 19 Energy as heat and electricity generated from each scenario.

There are several possible ways of using the energy produced by the different systems. In this thesis the produced energy in each plant was assumed to be electricity to make comparison between the systems easier. It might be more likely that the biogas from anaerobic digestion and from the landfill could be used as gas for cooking and household use. In countries with a demand for district heating or steam for industrial processes the produced energy, in the form of electricity and heat, can be utilized to a greater extent.

The efficiency in electricity production has a large impact on the amount of energy to heat and electricity. In the incineration scenario, it is assumed that the grate efficiency is 100 %, it might be likely that it is less, reducing the energy production. The spark ignition engines used in the landfill and anaerobic digestion scenario is assumed to have an electricity efficiency of 33 %. If another type of system for energy recovery system were used, like a gas turbine or a dual fuel diesel engine, both the efficiency and emissions would change (Williams, 2005).

The lower heating value has a large effect on the amount of energy produced in the incineration scenario. The LHV fluctuates slightly during the year, since the amount of water in the waste is higher during rainy seasons reducing LHV (Gilchrist, pers. comm). In order to raise the lower heating value, sawdust from sawmills in Kumasi could be added to the MSW prior to combustion.

7.2. GLOBAL WARMING POTENTIAL

The landfill contributed most in terms of global warming potential. The collection efficiency of landfill gas was assumed to be 50 %. If the efficiency were lower due to leakage through insufficient cover or broken pipes, the contribution would be higher (Figure 20).

The collection efficiency in the anaerobic digestion scenario was assumed to be 95 %. In large scale biogas plants it is not likely that as much as 5 % is leaking, so the GWP of anaerobic digestion was likely to be overestimated.

In the incineration scenario, all emissions contributing to the global warming category came from CO_2 from combustion of fossil carbon. The amount of carbon from fossil sources was estimated from the waste composition. This estimation has a large effect in the emissions of fossil CO_2 from incineration. If the waste is stored for a long time before combustion it is possible that anaerobic digestion of the organic matter in the waste would start, generating CH_4 as an effect. This is probably not a problem since storing of waste could lead to bad odor and attraction of rodents and insects.

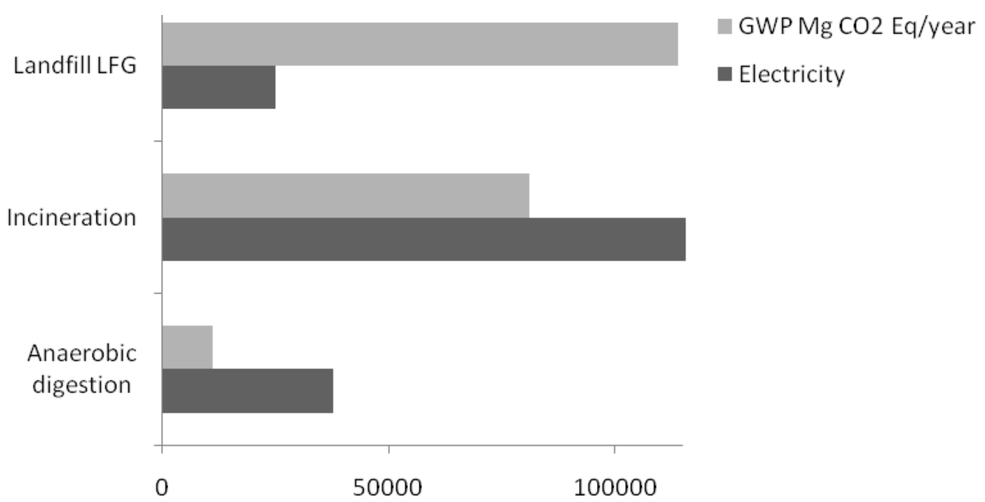

Figure 20 GWP and electricity produced in each scenario.

There was a large decrease in GWP compared to the present waste management system, i.e. landfilling without gas collection, in all other scenarios (Figure 21). The anaerobic digestion system reduced the GWP the most, by almost 90 %.

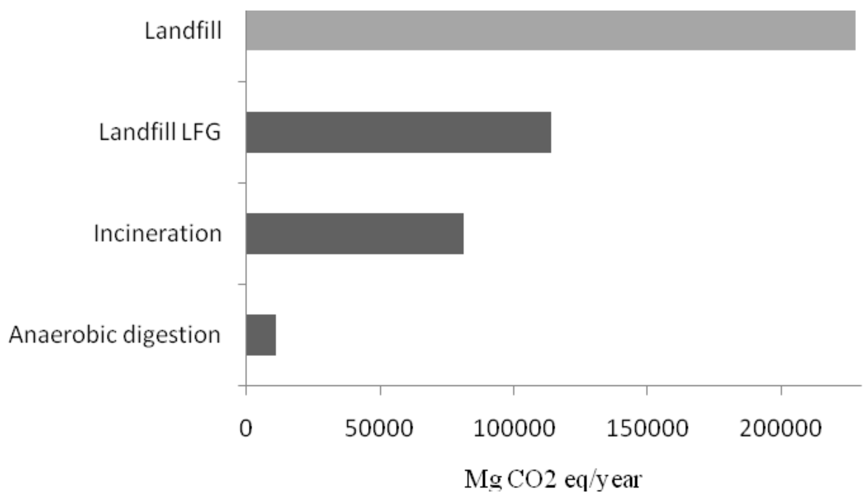

Figure 21 GWP in each scenario compared to the present waste management system used in Kumasi which is Landfill without gas collection.

The landfill scenario was modeled to generate gas from the waste amount generated during one year. Both electricity and emissions are calculated from this gas amount. However, the degradation in the landfill takes several years. The gas production was summed with the aim to compare the landfill scenario with the other scenarios, in which emissions occurs almost instantly. There was a high level of uncertainty in this calculation since the rate of degradation of organic matter and amount of gas produced in the landfill depends on many parameters. These are difficult to predict and they can change over time, depending on factors such as humidity, temperature, cover of landfill age of waste deposit among other factors.

7.3. ACIDIFICATION

The acid emissions were highest from incineration. These results have a high level of uncertainty since they were based on the general chemical composition of different waste fractions according to Magrinho et al. (2008). The choice of system and level of flue gas treatment is also a large error factor. The system which would be used by Cinergex Solutions Ltd would have a flue gas treatment with more than 80 % reduction of SO_2 and an outgoing NO_X level of less than 10 ppm in the flue gas (Gilchrist, pers. comm). It should be pointed out that the model of the incineration plant in this thesis was only partly based on the Cinergex Solutions Ltd system and that the results presented here do not necessarily correspond to the emissions from a future plant.

The emissions of NO_X and SO_2 from the diesel vehicles in the landfill are negligible in the context. These emissions are in the order of a couple of kg compared to several tons emitted by the different combustion processes (Table 16). The emissions from landfill management had a small impact compared to the emissions from each system.

7.4. SENSITIVITY ANALYSIS

There is a high level of uncertainty in the data used in the models. This is due to both the assumptions made where data is missing or difficult to implement in the model and to the reliability of existing data.

The sensitivity analysis shows that the evaluated parameters all have the same effect on the output parameters, with only smaller variations. The sources of uncertainties in the modeled scenarios are many and the sensitivity analysis shows that the estimated values have large impact on the output values.

The impact of most tested parameters was 1:1 linear. That is, one increase of 10% of an input parameter has a 10% impact on the result.

One aspect to consider is the level of flue gas cleaning from incineration and from gas combustion in the anaerobic digestion and landfill scenarios. The technology used has a large impact on the outcome of the study. The estimation of the waste compositions, easily degradable organic material and chemical composition is also a major source of uncertainty.

7.5. INCINERATION

The emissions from incineration were high in both impact categories considered. On the other hand the generation of electricity was noticeably higher in this scenario than in the other two.

One of the advantages of incineration is that the waste residue is minimized; the waste is reduced to approximately 10 % of the volume and 25 % of the weight before combustion (Combes, 2008). The ash is sterilized by the high temperature in the furnace and the ash can be used as filling material if the content of metals and other toxic substances and metals is not too high. There are ongoing Swedish studies about using incinerator ash to stabilize soil (Broberg, 2009).

Another advantage of incineration is the possibility to sort and reuse metals. This saves both resourses and reduces emissions to the surrounding environment. The metal sorting is easier to perform prior to incineration than before landfilling by using a magnetic or electro-magnetic separator (Meri, 2009). The incentive to sort metals is higher when incinerating MSW than in landfilling due to the fact that separation of inert material raises the energy output because of a higher LHV and a reduced risk of breakage. In both systems there is a motive in the gain in the market of reused metal. There is also an incentive for diverting concrete, drywall and glass from the waste stream prior to combustion since the presence of inert matter lowers the heating value, but also due to the limited recycling market for these products (Gilchrist, pers. comm).

The high temperatures in the incinerator destructs combustible toxins and pathogenically contaminated material. The negative aspect of incineration is the air pollution and waste water problems. Emissions from combustion of waste depend on the substances in the waste and on the technology used; temperature and equipment for flue gas and water treatment.

In incineration waste is combusted in a couple of seconds while waste deposited in a landfill takes decades to degrade. The fact that there is an inert residue, leads to a need of a landfill even in the incineration scenario. If there are metals in the ash and slag, toxic leakage from the landfill can lead to contamination of the surrounding environment.

Incineration of waste produces a lot of energy compared to the other two systems. If there is a need for electricity and/or heat, the cost of building an incineration facility often has a short payback time. On the other hand, the cost of investment and operation is high.

7.6. ANAEROBIC DIGESTION

Anaerobic digestion has many benefits compared to a landfill. The same process occurs in the digester as in the landfill, but in a controlled and monitored way. The degradation is faster, effluent water can be treated and the gas collection is more effective than it could be in a landfill site with gas collection. In a system for anaerobic digestion, it is also easier to separate recyclable waste, enabling reuse of metal and other valuable material.

The amount of waste is reduced when digested (Williams, 2005). One important benefit of anaerobic digestion is the possibility to retrieve nutrients to farming. In Kumasi, the level of P and N is ten times higher downstream the city compared to the levels upstream (Erni, 2008).

The system could reduce the demand for fossil fuels, since the generated gas can be used for cooking, as vehicle fuel or for production of heat and electricity.

The products from anaerobic digestion are all useful; the gas can be utilized for energy in different ways and the sludge as fertilizer or soil conditioner if it does not contain toxic substances. The effluent water is rich in nutrients and needs treatment before discharged. The process of digestion is effective in sanitizing of the digestive matter and can kill pathogenic bacteria and parasites in the feedstock.

The bacteria are sensitive to changes in pH, temperature and toxic substances. Variations in one or more of these parameters can reduce the gas production or terminate the process completely if the impact is too large (De Baere, 2006a).

The heat produced in generation of electricity can be used for processes and plant operation. Using the heat to evaporate the waste water from the plant minimizes pollution to water.

7.7. LANDFILL

The only benefit of landfill disposal is that it can manage all types of waste. The negative effects are many, need for large areas of land, risk of contamination of groundwater and emission of toxic, flammable gases. Methane is explosive and fires are common on landfill sites. This is a safety concern for people as well as a source for emissions. A lot of recyclable material is landfilled and the resources are not used. The production of new aluminum and other metal legations needs a lot of energy compared to reuse. This is a minor problem in developing countries where human scavengers are sorting the waste to utilize the waste fraction with a value, but on the other hand the scavengers are exposed to health threats by residing on landfill areas.

In all systems there is a need for a landfill, but in incineration and anaerobic digestion scenario there is only inorganic waste disposed, and therefore these systems will not lead to CH_4 emissions from landfilling. The fact that the residues are inorganic does not mean that there is no impact from landfilling them. Ash and slag from incineration often contain metals which can leak and contaminate water if they leak from the landfill site. It is not possible to separate organic and inorganic waste totally and therefore there will be a part of degradable organic matter in the landfilled waste separated from the anaerobic digestion scenario.

Regardless of uncertainties in parameter values, the study shows that landfilling is not a good option for waste management seen from an environmental view. Nevertheless, it is an inexpensive and easy way of ‘disposing’ waste used in many developing countries. CDM projects can be a way to reduce the use of landfills.

At existing landfill sites, collection of landfill gas reduces GWP, even if the gas is flared off and not used.

7.8. ALTERNATIVE WASTE MANAGEMENT

An alternative to the three methods considered is composting of the organic waste. Co-composting with sawdust or fecal sludge is a viable option. A lot of work has been done in this area, both in Kumasi by Mr Richard Koffour, (Mensah et al., 2003) among others and in Sweden (Sundberg, 2003). Since the scenarios compared were all assumed to generate electricity, composting was not considered.

In a future waste management in Kumasi, it is likely that the MSW would be co-treated with fecal sludge. Especially in the anaerobic digestion system co-treatment of organic waste and fecal sludge is beneficial for the biogas process since the C/N ratio is beneficial in that mixture, optimizing gas production (SDdimensions, 1997). Co-treatment would thereby expose more waste, both fecal and household waste, at the same time as the profit is raised due to a higher gas yield.

Another possible option is small scale biogas treatment, on household or possibly blocks level, where fecal sludge and organic household and yard waste are digested in the yards, generating gas for household use and nutrients for small scale agriculture.

The anaerobic digestion system is based on on-site separation of waste. Another possible scenario is to separate the organic waste at household level. Studies have been preformed of household separation showing a potential for source separation at household level in Kumasi in the future (Asase et al, 2009).

7.9. MODEL EXTENSIONS

This study focused on electricity production and two impact categories: GWP and acidification. Since all impact categories were not included, the total environmental impact of each system has not been evaluated. To evaluate the total environmental impact of a system, all processes in the waste management chain must be considered, from production of parts to the plant, effect and emissions from construction, transports, and chemicals used in treatment of effluents to air and water, disposal of residues and eventually even demolition of the plant.

No consideration was taken to process water treatment. This would be of great interest in further studies. Addition of chemicals in the processes should be added to the evaluation, such as lime for flue gas treatment, ammonia in SO_2 flue gas treatment and eventual flocculation chemicals in water treatment among others. Modeling of nutrients and eutrophication effect of each scenario is also an interesting possible extension of the model.

Emissions of N_2O and CO was neglected. N_2O is 310 times as potent as CO_2 in terms of GWP. CO is a poisonous gas, affecting the central nervous system. It forms in combustion with reduced availability to oxygen. Modern incinerators operate in excess of oxygen to prevent the formation of CO (EPA, 2009). N_2O is formed in composting organic material (Kroeze, 1994). In further studies it is of value to evaluate the possible impact of these gases.

Besides more studies of the negative effects of each scenario, it would be interesting to evaluate the potential benefits with each system. There could be a possibility to use incinerator ash for construction and stabilization and the sludge from anaerobic digestion as a fertilizer on the fields.

Time is an important aspect when choosing a system for waste management since both population and economic growth changes the waste stream. It is important to dimension the facility to suit the supply of waste. Factors such as population growth, change of habits and increase of GDP can generate more waste and possible less of the organic fraction.

Besides the environmental aspects, other important considerations must be considered such as cost of installation and maintenance of each plant, but also social and cultural aspects to raise the chance of proper management of the facility.

7.10. CONCLUDING COMPARISON OF SYSTEMS

The conclusions which could be drawn from the modeling were:

1. The modeled electricity generation was highest from the incineration scenario with a large margin towards the other scenarios.
2. The anaerobic digestion had the lowest modeled emissions in the GWP category.
3. The landfill scenario had the lowest modeled impact in the acidifying category compared to the other scenarios.

When choosing a system for waste management there are many factors to consider. To ensure the sustainable function of a waste management project, factors such as technical, economic, institutional and social must be considered. All of these factors contribute to the long term achievement of a waste management system. It is important to involve people in the recipient country when a waste to energy plant is built as CDM project. If not, there is a risk that the plant is not operated in a safe and durable manner. In Kumasi, solid waste management is improving each year on incentive from the Kumasi Metropolitan Assembly, Waste Management Department and also because waste collection is outsourced on private companies such as ZoomLion.

Important aspects to consider when evaluating waste management systems are economic aspects. If solid waste could be used to produce energy, the incentive to collect it will be greater. In Kumasi, waste collection is improving fast. There is also a great demand for an increased energy production in Ghana. The incineration system is superior in electricity production. The large electricity production appeals both to the economic aspect and to the fact that Ghana and Kumasi have a large electricity demand to cover. Continuous electricity supply is important for the continued economic growth of the country since electricity is needed for most of the important financial sectors of the economy. Proper waste management does also have an impact on the economic growth of a country since dumped waste affects societies indirectly by negatively affecting human health.

One conclusion that could be drawn is that none of these systems are only beneficial from an environmental perspective; they all have their benefits and negative effects. In comparison to dumping, burning and uncontrolled landfill disposal, all of the methods reduce the GWP, but not the emissions of NO_X and SO_2. On the other hand, CH_4 is very flammable and fires on dumpsites are quite common leading to emission of acid and toxic gases. A fact is also that the solid waste needs to be managed. By generating energy and electricity from the waste in a controlled way, the energy is utilized and the waste is turned from a problem into a resource. By generating electricity from waste, it is often possible to reduce the use of fossil fuels like coal and oil used for energy purposes, thereby reducing global warming potential.

All of the scenarios were good options when comparing them to the generation of electricity from fossil sources like coal or oil. These fossil fuels have an impact of 815 and 935 kg CO_2/MWh electricity, respectively (NEI, 1998). Especially the incineration scenario would reduce the emissions of CO_2 per produced unit of electricity showing emissions of 425 kg CO_2/MWh of electricity. The modeled incineration plant would save 97 000 ton CO_2 per year compared to production of the same amount of electricity from oil.

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APPENDIX 1 ORWARE VECTOR

```
ORWAREVECTOR =[

         0    % 1  C-tot          Total carbon
         0    % 2  C-chsd         Carbon in slowly degradable organics
         0    % 3  C-chfd         Carbon in rapidly degradable carbohydrates
         0    % 4  C-fat          Carbon in fat
         0    % 5  C-Protein      Carbon in protein
         0    % 6  BOD            Biological oxygen demand 7
         0    % 7  VS             Volatile solids
         0    % 8  DM             Dry matter
         0    % 9  CO2f           Carbon dioxide of fossil origin
         0    % 10 CO2b           Carbon dioxide of biological origin
         0    % 11 CH4            Methane
         0    % 12 VOC            Volatile organic compounds
         0    % 13 CHX            Halogenated hydrocarbons
         0    % 14 AOX            Adsorbable organic halogens
         0    % 15 PAH            Polyaromatic hydricarbons
         0    % 16 CO             Carbon monoxide
         0    % 17 Phenols
         0    % 18 PCB            Polyclorinated biphenyls
         0    % 19 Dioxin
         0    % 20 O-tot          Oxygen, except in H2O
         0    % 21 H-tot          Hydrogen, except in H2O
         0    % 22 H20            Water
         0    % 23 N-tot          Total nitrogen
         0    % 24 NH3/NH4        Nitrogen in ammonia or ammonium
         0    % 25 N-NOX          Nitrogen in nitrogen oxides
         0    % 26 N-NO3          Nitrogen in nitrate
         0    % 27 N-N2O          Nitrogen in dinitrogen oxide
         0    % 28 S-tot          Total sulphur
         0    % 29 S-SOX          Sulphur in sulphur oxide
         0    % 30 P              Phosporous
         0    % 31 Cl             Cloride
         0    % 32 K              Potassium
         0    % 33 Ca             Calcium
         0    % 34 Pb             Lead
         0    % 35 Cd             Cadmium
         0    % 36 Hg             Mercury
         0    % 37 Cu             Copper
         0    % 38 Cr             Chromium
         0    % 39 Ni             Nickel
         0    % 40 Zn             Zink
         0    % 41 C-chmd         Carbon in moderately degradable organics
         0    % 42 Particles      Particles in gas
         0 ]; % 43 COD            Chemical oxygen demand
```

APPENDIX 2 EXAMPLE OF CALCULATION IN MODEL

```
% Created by Emma Wikner 2009-04-09

function y =
IcAirEmission(u,IcNOXFrac,IcSO2Frac,IcCO2fFrac,IcCO2bFrac,IcCH4Frac)
% Returns a vector with the gas composition of landfill gas

y = [u(1)-((u(1)*IcCH4Frac)+(u(1)*IcCO2fFrac)+(u(1)*IcCO2bFrac))
    u(2:8)
    u(9)+(u(1)*IcCO2fFrac)
    u(10)+(u(1)*IcCO2bFrac)
    u(11)+(u(1)*IcCH4Frac)
    u(12:22)
    u(23)-(u(23)*IcNOXFrac)
    u(24)
    u(25)+(u(23)*IcNOXFrac)
    u(26:27)
    u(28)-(u(28)*IcSO2Frac)
    u(29)+(u(28)*IcSO2Frac)
    u(30:43)];
```

APPENDIX 3 CALCULATION OF LOWER HEATING VALUE

Table A1 Chemical components of waste fractions (Magrinho et al., 2008) and LHV of MSW in Kumasi

Waste part	Fraction of component (%)	m(w) (%)	m(c) (%)	m(h) (%)	m(o) (%)	m(n) (%)	m(s) (%)	LHV (MWh/ton)
Food	5	75	11.68	2	9.72	0.53	0.03	0.04
Paper/cardboard	5	23	33.11	5.39	33.88	0.15	0.02	0.17
Plastic	11	20	48	8	18.24	0	0	0.67
Textiles	1	10	49.5	5.94	28.08	4.05	0.18	0.05
Wood	6	20	39.2	4.8	34.16	0.16	0.08	0.23
Yard	60	65	16.73	2.1	13.3	1.19	0.11	0.79
Rubber and leather	4	10	48.42	8.01	20.97	0.75	0.51	0.25
Metals	2	3	4.37	0.58	4.17	0.1	0	0.01
Inerts	6	0	0.00	0.00	0.00	0.00	0.00	0.00
								2.228

Equation A1 was used to calculate the LHV for the different fractions of waste.

$$LHV_{Wet\ basis} = 4.187 * [81C + 300H - 26(O - S) - 6(9H + W)] \qquad \text{(A1)}$$

Where C, H, O, S and W are the amount of carbon, hydrogen, oxygen, sulphur and water in the MSW respectively. The LHV is calculated for each fraction of waste (Table 8) and then added to receive total LHV.

APPENDIX 4 GENERAL INPUT DATA

Values of general input data to all models

Input data	Value	Description
MSW	-	Matrix containing one ORWARE vector for each component of waste
OrganicWaste	Food+Yard	Amount of organic waste(ton/day)
WasteProd	1100 ton/day	Amount of waste produced in Kumasi per day
CollectionEff	0.70	Collection efficiency, part of produced MSW collected (Mensah et al., 2008)
CH4CO2eq	21	CH4 gives 21 times more impact in the category GWP (IPPC, 2000)
NOXSO2eq	0.7	NOX has an acidifying effect of 0.7 times SO2 (Baumann et al., 2004)
LfCO2fManagement	3.565E-3	Ton fossil CO2/ton MSW (ORWARE, Landfill),(OKQ8, 2006) Fossil CO_2 from diesel vehicles operating landfill
LfNOXManagement	5.217E-8	Ton NO_X/ton MSW, (OKQ8, 2006) NO_X from diesel vehicles operating landfill
NOXperN	46.01/14.1	Weight of NOx emitted per N to NO_X
SO2perS	64.1/32.07	Weight of SO_2 emitted per s to SO_2
CO2perC	44/12	Weight of CO_2 emitted per C to CO_2
CH4perC	32.016/12	Weigt of CH_4 emitted per C to CH_4

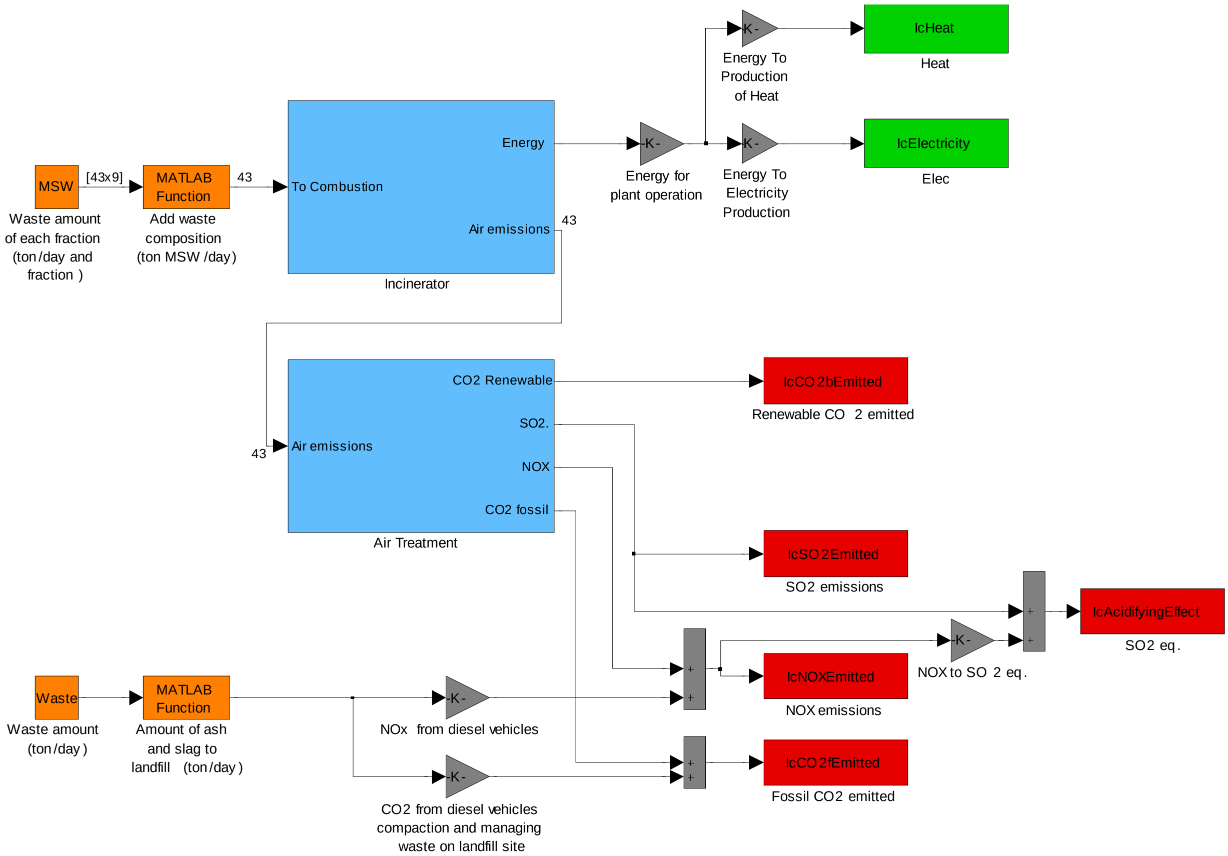
APPENDIX 5 INPUT DATA FOR INCINERATION MODEL

Values for input data used in the Incineration scenario

Input data	Value	Description
IcEfficiencyEl	0.38	Efficiency in electricity production (CEWEP, 2004)
IcEfficiencyHeat	1-IcEfficiencyEl	
IcEnergyOperation	0.20	Part of produced energy needed for operation if plant (Twence, 2008)
IcEfficiency	1	Efficiency of combustion, based on (UFC, 2004)
IcNOXReduction	0.60	Reduction of NOX 60 % efficient (Energiochmiljo, 2002)
IcSO2Reduction	0.80	Reduction of NOX 90 % efficient (Energiochmiljo, 2002)
IcNOxFrac	0.10	NOX per N in MSW incinerated (Johansson, pers. comm)
IcSO2Frac	0.95	SO2 per S in MSW incinerated Estimation based on (Johansson, pers. comm)
IcCO2fFrac	0.35	Part of C in gas to fossil CO_2
IcCO2bFrac	0.65	Part of C in gas to renewable CO_2
IcCH4Frac	0	Part of C in gas to CH_4, assumed that no CH_4 is generated
IcAsh	0.05	Ash produced per ton MSW incinerated (ton/ton). Assumption made based on that ash and slag together add up to 25 of weight of incoming waste (CHAPTER 18, Municipal Waste Combustion, 2008)
IcSlag	0.20	Assumption based on CHAPTER 18, Municipal Waste Combustion, 2008.

APPENDIX 6 MODEL FOR INCINERATION SCENARIO

MATLAB Simulink model of incineration scenario



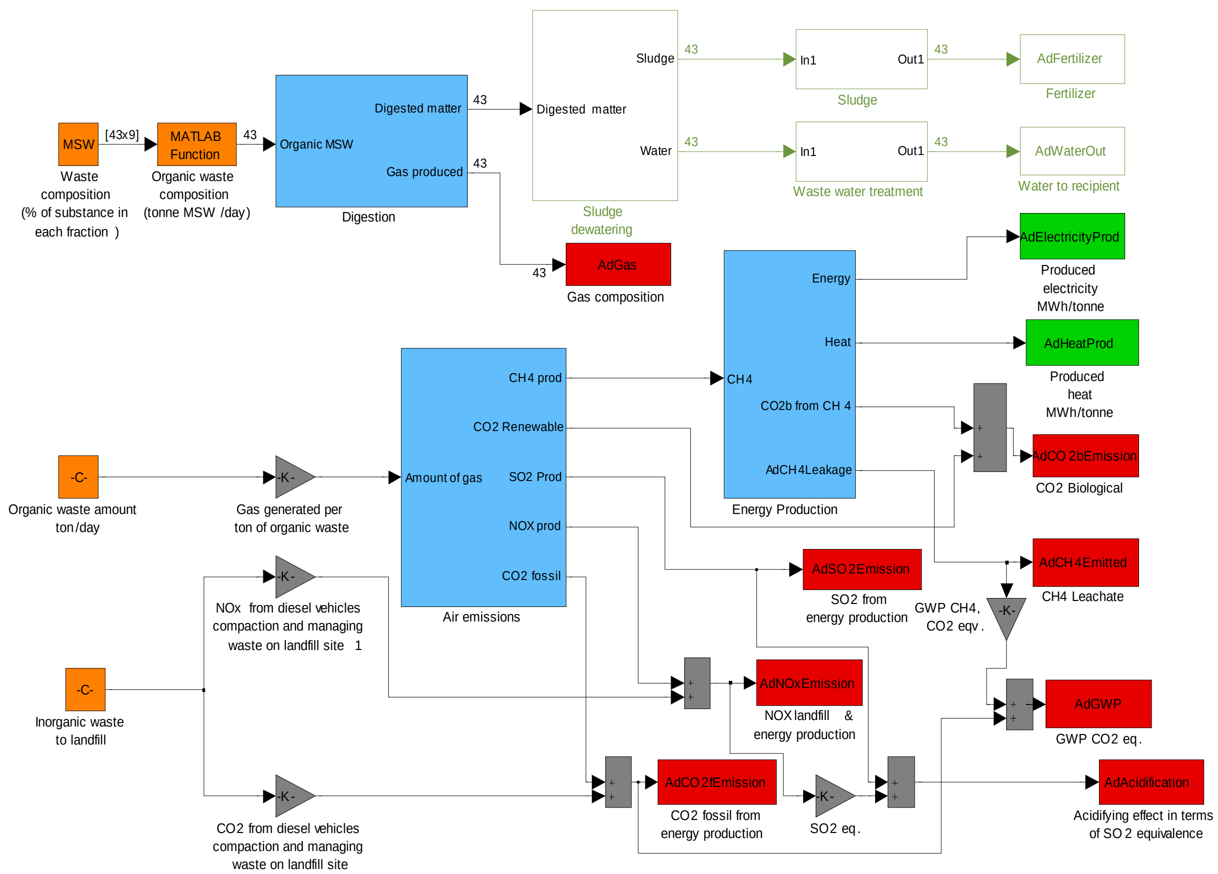
APPENDIX 7 INPUT DATA FOR ANAEROBIC DIGESTION MODEL

Values for input data used in the Anaerobic Digestion scenario

Input data	**Value**	**Description**
AdEfficiencyEl	0.33	Efficiency in electricity production (Electrigaz, 2006)
AdEnergyOperation	0.20	Part of produced energy needed for operation if plant (IEA Annual Report, 2004)
AdCH4Leakage	0.05	Part of CH_4 not collected
AdGasProd	150	Nm^3 gas per ton organic waste, estimation based on (Williams, 2005) and (JG Press, 2007)
AdCH4Energy	0.0010	MWh/Nm^3 of CH_4 (Svenska gasföreningen, 2009)
AdNOxFrac	1170	mg/Nm^3 gas (Williams, 2005)
AdSO2Frac	22	mg/Nm^3 gas (Williams, 2005)
AdNOXReduction	0	No NO_X reduction assumed
AdSO2Reduction	0	No SO_2 reduction assumed
AdCH4Frac	0.55	55 % CH_4 in gas
AdCO2bFrac	0.44	44 % CO_2 in gas
Ad CO2fFrac	0	0 % fossil CO_2

APPENDIX 8 MODEL FOR ANAEROBIC DIGESTION SCENARIO

MATLAB Simulink model of anaerobic digestion scenario



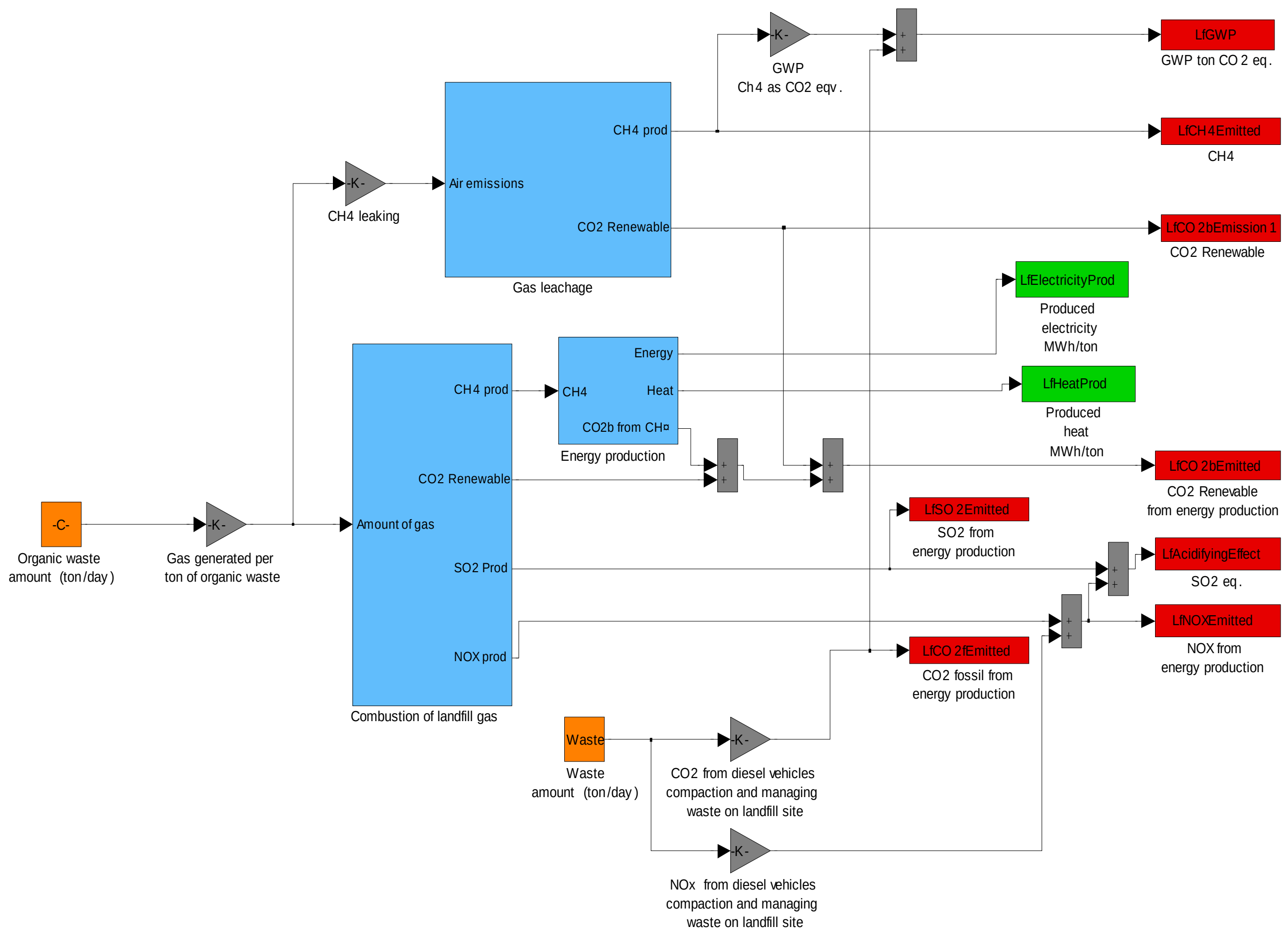
APPENDIX 9 INPUT DATA FOR LANDFILL MODEL

Values for input data used in the Landfill scenario

Input data	Value	Description
LfEfficiencyEl	0.33	Efficiency in electricity production (Electrigaz, 2006)
LfCO2fManagement	3.56544E-3	Fossil CO_2 emitted when operating landfill (ton CO_2/ton MSW) (OKQ8, 2006)
LfNOXManagement	5.217E-8	(ton NO_X/ton MSW) (OKQ8, 2006)
LfCH4CollectionEff	0.50	Part of CH_4 collected (Williams, 2005)
LfSO2Reduction	1	No SO_2 treatment assumed
LfNOXReduction	1	No NO_X treatment assumed
LfGasProd	150	Nm^3 gas per ton organic waste, estimation based on (Williams, 2005) and (JG Press, 2007)
LfNOxFrac	1170	mg/Nm3 gas (Williams, 2005)
LfSO2Frac	22	mg/Nm3 gas (Williams, 2005)
LfCO2fFrac	0	Part of C in gas to fossil CO_2
LfCO2bFrac	0.44	Part of C in gas to renewable CO_2, estimation based on (Williams, 2005)
LfCH4Frac	0.55	Part of C in gas going to CH_4, estimation based on (Williams, 2005)

APPENDIX 10 MODEL FOR LANDFILL SCENARIO

MATLAB Simulink model landfill scenario



APPENDIX 11 MODEL CALCULATIONS

$$Org = MSW * (1 - (Yard + Food)) \quad (1)$$

Where,

Org = Organic part of MSW
Yard = Yard fraction of MSW
Food = Food fraction of MSW

Methane production
Calculates the amount of CH4 generated per ton of organic solid

$$X_{m,CH_4} = E_{Prod} * CH_4c * Org \quad (2)$$

Where,

X_{m,CH_4} = Volume of CH_4 produced
E_{Prod} = Estimated gas production per ton organic solid
CH_4c = Content of CH_4 in gas

Electricity production in anaerobic digestion scenario;

$$El_{Prod} = (X_{m,CH_4} - G_L) * (1 - E_{Operation}) * El_{eff} * Energy_{CH_4} \quad (3)$$

Where,

G_L = Part of gas leaking
$E_{Operation}$ = Part of energy for plant operation
El_{eff} = Efficiency in electricity production
$Energy_{CH_4}$ =Energy produced per ton of CH_4

Electricity production in landfill scenario;

$$El_{Prod} = X_{m,CH_4} * k * El_{eff} * Energy_{CH_4} * (1 - G_L) \quad (4)$$

Where,

X_{m,CH_4} = CH4 produced per ton of organic MSW
k = Decay rate, digestion of organic material per year
El_{eff} = Efficiency in electricity production
$Energy_{CH_4}$ =Energy produced per ton of CH_4
G_L = Part of gas leaking

Electricity production in incineration scenario;

$$El_{Prod} = LHV * El_{eff} * MSW \quad (5)$$

Where,

LHV = Lower heating value (MWh/Mg)
El_{eff} = Efficiency in electricity production
MSW = Mass of waste incinerated

<u>GWP;</u>

$$CO_{2\,Equivalence_r} = \left(21 * m_{CH_4} * V_{CH_4}\right) + CO_{2\,fossil} \qquad (6)$$

Where,

m_{CH_4} = 0.72 kg/Nm^3 (Levin et al., 2006)
V_{CH_4} = Volume of CH_4 emitted

<u>Acidification;</u>

$$SO_{2\,Equivalence_r} = \left(0.7 * M_{NO_X}\right) + SO_2 \qquad (7)$$

Where,

M_{NO_X} =Mass of NO_X emitted

<u>Calculation of landfill vehicle emissions;</u>

$$CO_{2_{Vehicles}} = Fuel * MSW * CO_{2_{fuel}} \qquad (8)$$

Where,

Fuel = Volume of diesel per Mg waste landfilled (m^3)
MSW = Amount of waste landfilled (Mg)
$CO_{2_{fuel}}$ = CO_2 emitted per m^3 of diesel combusted

$$NO_{X_{Vehicles}} = Fuel * MSW * NO_{X_{fuel}} \qquad (9)$$

Where,

Fuel = Volume of diesel per Mg waste landfilled (m^3)
MSW = Amount of waste landfilled (Mg)
$NO_{X_{fuel}}$ = NO_X emitted per m^3 of diesel combusted