Municipal Solid Waste Characterization for Waste-to-Energy Management in Harare Metropolitan Province, Zimbabwe

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ABSTRACT

Waste-to-Energy (WtE) has gained popularity world over as a tool for assisting municipalities to reach waste management goals. The availability of data on the physical and chemical characteristics of municipal solid waste (MSW) as a potential feedstock for WtE recovery is critically important for planning purposes. In the current study, for the first time the MSW in Harare metropolitan province is examined in view of its potential as a fuel for WtE conversion. The study comprehensively focusses on selecting the most sustainable WtE technology to apply in the context of Harare. First, the metropolitan area's waste management system is evaluated through material flow analysis (MFA) and concluded to be weak and highly ineffective. Secondly, the MSW is sampled and analysed onsite for physical composition and bulk density. Samples are collected for further preparation and laboratory analyses. Scenario modelling is then applied in order to assist in WtE technology selection from five alternatives. The model is built and evaluated using multi-criteria decision analysis (MCDA) software which gives the final ranking of options. Energy content analysis showed that the MSW has a lower heating value of 10.1 MJ/kg making it ideal for thermochemical processing with minimal pre-treatment. The moisture content ranged from 30 to 36% with the mean for the province being 34%. The elemental composition of the waste is given as 47% C, 4.9% H, 33% O, 2.2% N, 0.8% S and 0.6% Cl. The study showed that the MSW can be treated by thermochemical or biochemical means without requiring supplementary fuel. Techno-economic, environmental and social sustainability considerations made through scenario modelling conclude that landfill gas to electricity can bring optimal benefits to Harare Province's waste management system. Therefore, this study provides critical data essential for waste management planning.

Keywords: Multi-criteria Decision Analysis (MCDA), Municipal Solid Waste (MSW), MSW Characterization, Waste Management System, Waste-to-Energy (WtE)

ชื่อวิทยานิพนธ์ คุณลักษณะของขยะมูลฝอยชุมชนสำหรับการจัดการแปรรูปขยะเป็นพลังงานในเขตเทศบาลเมืองฮาราเร่ ประเทศซิมบับเว

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ปีการศึกษา 2560

บทคัดย่อ

การแปรรูปขยะเป็นพลังงานได้รับความนิยมอย่างแพร่หลายทั่วโลก ช่วยในการบรรลุเป้าหมายการจัดการขยะมูลฝอยของเทศบาล ความพร้อมของข้อมูลเกี่ยวกับลักษณะทางกายภาพและทางเคมีของขยะมูลฝอยชุมชนของเทศบาล (MSW) ซึ่งเป็นวัตถุดิบที่มีศักยภาพสำหรับการแปรรูปขยะเป็นพลังงาน (WtE) เป็นสิ่งสำคัญอย่างยิ่งสำหรับการวางแผนการจัดการขยะของเทศบาล ในการศึกษาวิจัยนี้ เป็นครั้งแรกที่ขยะมูลฝอยชุมชนในเทศบาลเมืองฮาราเร่ (Harare) ได้รับการพิจารณา เนื่องจากมีศักยภาพในการใช้เป็นเชื้อเพลิงสำหรับการแปลงเป็นพลังงาน การศึกษามุ่งเน้นการคัดเลือกเทคโนโลยีแปรรูปขยะเป็นพลังงานอย่างยั่งยืนเพื่อใช้ในบริบทของเมืองฮาราเรอย่างครอบคลุม ประการแรก ระบบการจัดการขยะของเขตพื้นที่ได้รับการประเมินโดยการวิเคราะห์ผ่านกระบวนการการไหลของวัตถุดิบ (Material Flow Analysis - MFA) และได้ข้อสรุปว่าระบบการจัดการขยะมูลฝอยยังมีข้อจำกัดและขาดประสิทธิภาพเป็นอย่างมาก ประการที่สอง ขยะชุมชนถูกสุ่มตัวอย่างและผ่านการวิเคราะห์คุณสมบัติทางกายภาพและความหนาแน่น ตัวอย่างถูกเก็บเพื่อเตรียมและวิเคราะห์ในห้องปฏิบัติการ จากนั้นจึงประยุกต์ใช้โมเดลสถานการณ์จำลองเพื่อช่วยในการคัดเลือกเทคโนโลยีการแปรรูปขยะเป็นพลังงานที่เหมาะสมจาก 5 เทคโนโลยีทางเลือก แบบจำลองถูกสร้างขึ้นและประเมินโดยใช้ซอฟต์แวร์การวิเคราะห์การตัดสินใจแบบพิจารณาหลายเกณฑ์ (Multi-criteria Decision Analysis - MCDA) ซึ่งให้ทางเลือกตามลำดับความสำคัญ การวิเคราะห์ด้านพลังงานเชิงเนื้อหา (Energy Content Analysis) แสดงให้เห็นว่าขยะมูลฝอยชุมชนให้ค่าพลังงานความร้อนต่ำ (Lower Heating Value – LHV) เท่ากับ 10.1 เมกะจูลต่อกิโลกรัมขยะชุมชน ทำให้มีความเหมาะสมต่อการแปรรูปขยะเป็นพลังงานด้วยการใช้ความร้อน โดยผ่านการแปรรูปขั้นต้นน้อยที่สุด ความชื้นของขยะมูลฝอยชุมชนอยู่ในช่วงร้อยละ 30 - 36 โดยมีค่าเฉลี่ยอยู่ที่ร้อยละ 34 มีองค์ประกอบหลักทางเคมี ประกอบด้วย คาร์บอน ร้อยละ 47, ไฮโดรเจน ร้อยละ 4.9, ออกซิเจน ร้อยละ 33, ไนโตรเจน ร้อยละ 2.2, ซัลเฟอร์ ร้อยละ 0.8 และ คลอรีน ร้อยละ 0.6 ผลการศึกษาพบว่าขยะมูลฝอยชุมชนสามารถบำบัดด้วยกระบวนการใช้ความร้อนทางเคมีหรือบำบัดด้วยวิธีทางชีวเคมีโดยไม่ต้องใช้เชื้อเพลิงเสริม การสร้างแบบจำลองสถานการณ์สมมติ (MDCA) คำนึงถึงความยั่งยืนทางเศรษฐกิจ สิ่งแวดล้อม และสังคม สรุปได้ว่าการฝังกลบก๊าซเพื่อการผลิตไฟฟ้าสามารถนำมาซึ่งผลประโยชน์สูงสุดให้กับระบบการจัดการขยะของเทศบาลเมืองฮาราเร ดังนั้นการศึกษานี้จึงแสดงข้อมูลสำคัญที่จำเป็นสำหรับการวางแผนการจัดการขยะมูลฝอยชุมชนของเมืองต่อไป

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Dedication

His mercy and kindness…

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LIST OF ACRONYMS

AD- Anaerobic digestion

AHP- Analytical hierarchy process

CBA- Cost benefit analysis

CH_4: Methane

CHP-Combined heat and power

CO_2: Carbon dioxide

EMA- Environmental Management Agency

FIT-Feed-in-Tariff

GHG- Greenhouse gases

GOZ-Government of Zimbabwe

IES- Institute of Environmental Studies in Zimbabwe

ISWMP- Integrated solid waste management plan

KW- Kilowatt (also the multiples Megawatt/Gigawatt/Terawatt are used)

KWh- Kilowatt hours (also the multiples Megawatt hours/Gigawatt hours/Terawatt hours are used)

LCA- Life cycle assessment

LFG- Landfill gas

MCA-Multi-criteria analysis

MCDA-multi-criteria decision analysis

MFA- Material flow analysis

MJ/kg-Mega joules per kilogram

MSW- Municipal solid waste

MT-Metric tonne(s)

NMOC-non methane organic compounds

OECD- Organization for Economic Cooperation and Development

RDF- Refuse derived fuel

USE-EPA- United States Environmental Protection Agency

WMS- waste management system

WtE- Waste-to-energy

ZETDC- Zimbabwe Electricity Transmission and Distribution Company

ZIMASSET- Zimbabwe Agenda for Sustainable Socio-Economic Transformation

ZNSA- Zimbabwe National Statistical Agency

CHAPTER 1

INTRODUCTION

1.1. Background

Expanding global human population, increased urbanization and technological advancement have not only meant an increased demand for energy, but also an increased generation of solid waste. Added concerns about increased over-reliance on fossil fuels have caused widespread demand to increase the renewable energy share in the primary energy supply mix. Modern waste treatment has therefore come as not only a way to deal with the growing volumes of waste, but also a means of producing heat and electricity to supplement traditional supplies and increase the renewable energy share in the energy supply mix.

At least 80 % of the energy used on earth today is derived from fossil fuels (Tester, Drake, Driscoll, Golay, & Peters, 2012). Global energy concerns have expanded over the years to include not only worry over this finite nature of fossil fuels but also the impact of their exploitation, distribution and use on the environment. The world coal consumption rose from 2,099 million tonnes per year in 1986 to 3,839.85 million tonnes per year in 2015 (BP, 2016). In contrast, the renewable energy fraction grew to a meagre 3% of the total primary energy share and 6.7 % of the global electricity generation by 2015 (BP, 2016). Even though the figure represents some commendable progress, it shows that a lot more has to be done to reduce heavy dependence on fossil fuel. For that reason, any additional stream of renewable energy, including energy from wastes, is a noble initiative to buttress efforts for increased renewable energy content in the energy mix.

Globally, per capita solid waste generation was estimated at 1.3 billion tons in 2012 and is projected to increase to 2.2 billion tons by 2025 (World Bank, 2012) exerting more pressure to the responsible authorities. OECD member states lead the world in municipal solid waste generation contributing almost half of the global solid waste (Fig. 1.1). The

United States, Brazil, China, India and Mexico lead the top ten countries with the highest MSW generation rates most certainly because of their high population and high standards of lifestyle for the urban populace where most of the MSW originates. Africa's contribution to the global MSW share is relatively small, with an estimated 62 million tons per annum (World Bank, 2016). Sub Saharan Africa per capita solid waste generation ranges from 0.09 to 3.0 kg/person/day with an average of 0.65 kg/person/day (World Bank, 2012).

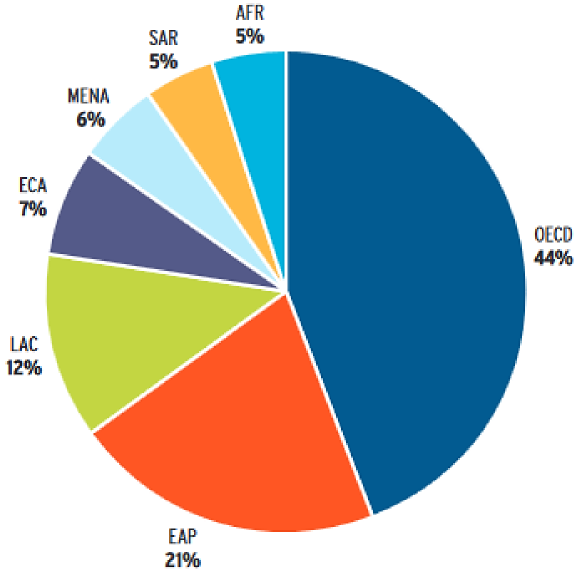
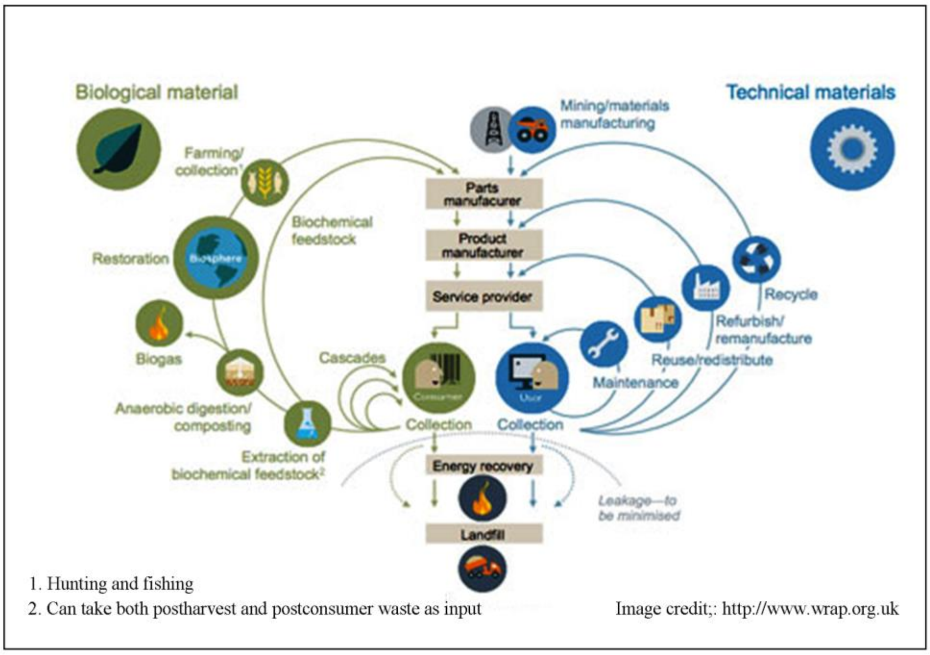


Fig. 1.1 Global waste generation by region in 2012

OECD: Organization for Economic Cooperation and Development, AFR: Africa South of Sahara, SAR: Special Administrative Region: MENA: Middle East and North Africa, ECA: Europe and Central Asia, LAC: Latin America and the Caribbean, EAP: East Asia Pacific)

Source: (World Bank, 2012)

The objective of modern waste management has shifted from waste disposal to supplying the economy with secondary raw materials and energy recovered from wastes (Malinauskaite et al., 2017). This is the philosophy of the circular economy (Fig 1.2). In many developed countries including the EU, waste management policy reforms have already been made to facilitate a transition towards the circular economy where the per capita waste generation is on an infinite decline, and waste is regarded as a resource. Waste to energy has therefore become an interesting option for many nations in trying to solve both the waste problem, while at the same time generating substantial amounts of energy that can supplement traditional supplies. Municipal solid waste plants have evolved from the mere mass burn plants of the late 19th century to more sophisticated plants with emission control mechanisms available today. With the majority of waste being generated by the developed countries, it is relieving to notice that the majority of WtE plants are in these countries. Although the MSW generated in Africa represents just about an eighth of the global production (Scarlat et al, 2015), the environmental and health impacts associated with the disposal of this waste are immeasurable.



1. Hunting and fishing
2. Can take both postharvest and postconsumer waste as input

Image credit;: http://www.wrap.org.uk

Fig. 1.2 Flows of materials in a circular economy

Zimbabwe has not been spared from the challenges faced by the rest of Africa. With a population that almost doubled over the last two decades (ZNSA, 2015), the resulting energy demand has increased and pressure on services increased as well. Waste volumes generated equally increased and in almost all urban areas exceeded the capacity of local authorities to deal with the problem. Waste collection dropped from 80% in the 1990s to 30% in 2012 while the recycling was only 3% in 2011 (Tsiko and Togarepi, 2012). These volumes of waste some of which are dumped in the open environment without adequate pollution control measures can be converted into valuable energy. Unfortunately, to date, the value of Zimbabwe's MSW as a source of energy had not been evaluated.

Attempts to estimate the waste energy potential for Africa has been done by Scarlat et al, (2015) but the study was affected by unavailability of data from many African countries. The WtE potential of Zimbabwe had therefore been only generalized. Tsiko & Togarepi, (2012) made effort to characterize the municipal waste in Harare metropolitan province. However nothing had been done to relate the findings to the MSW's value as a potential alternative energy resource. In addition, data used by Tsiko and Togarepi (2012) dated back to year 2000 and 1995 being data collected by MLGRUD, (1995). Zimbabwe went through massive socio-economic changes over the past 2 decades which have undoubtedly altered the lifestyles of the populace and the respective trading and consumption patterns, hence resulting in changes in the MSW composition over the years. For example, the severe economic hardships that bedevilled the country at the height of the hyper-inflationary environment in 2007-2008 saw the collapse of the local manufacturing industry. This led to massive importation of goods from neighbouring countries as well as an influx of products from Asian countries including China and Dubai. Additionally, in 2010 and 2011, the country's environmental regulatory authority, EMA introduced a ban on manufacture, importation or commercial distribution of plastic packaging of thickness less than 30 micrometres. In 2017 EMA banned the use of expanded polystyrene (kaylites) packaging on food products (EMA, 2017b). This undoubtedly impacted on the level of packaging as well as the consumption pattern of the country and had a significant bearing on the composition of MSW generated in the various urban areas.

The government of Zimbabwe consulted the University of Zimbabwe’s Institute of Environmental Studies (IES) to conduct a nationwide solid waste baseline survey in 2011 (IES, 2013). The extensively conducted survey made available data on solid waste quantities and composition by sector (industrial, commercial, residential etc.) as at 2011. Findings of the study led to formulation of the Zimbabwe Integrated Solid Waste Management Plan (ISWMP) in 2014 which proposed among many other options the need to explore and promote the use of solid waste as a resource for energy recovery. Unfortunately, to date, such exploration had never been done and the waste management situation continued to worsen as revealed by a follow-up survey conducted for Harare by EMA, (2016).

This study therefore sought to closely examine the municipal solid waste generated in Harare metropolitan province, Zimbabwe in the context of its value as an alternative energy resource. Material flow analysis was used as the primary tool for evaluating the flows and stocks of MSW in the province. A scenario analysis was performed in this study for Harare metropolitan province, Zimbabwe in the contest of six different scenarios, to predict with reasonable assumptions resulting impact on LFG emissions, landfill lifespan, energy output among other technical, economic, environmental and social parameters for a 10 year period: 2017-2027. The scenarios are based on waste management options preferred and include disposal of total volume of the MSW in landfill without LFG capture (the business as usual approach), incineration with energy recovery (MSWI) for electricity generation, refuse derived fuels (RDF) for electricity co-generation with coal, anaerobic digestion (AD) with biogas and digestate utilization and LFG to electricity. The sixth alternative was a hybrid plant comprising AD and MSWI. The broad aim of the study was to determine the most sustainable options for WtE management in the area under investigation. By sustainable, that demanded an address to the question of cost-effectiveness, environmental sustainability and social sustainability (Santoyo-Castelazo & Azapagic, 2014)

Definition of key terms

MSW- Municipal solid waste refers to the entire proportion of everyday items people use and throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries (US EPA, 2016) and may comprise of waste generated from residential, commercial, institutional and public parks (Ng, Lam, Varbanov, & Klemeš, 2014)

Waste to energy (WtE) is conversion of liquid or solid waste materials into energy in the form of heat or electricity by various thermo-chemical and biochemical processes including incineration, pyrolysis, gasification, thermal carbonization, anaerobic digestion and fermentation. Some definitions specify waste used as non-recyclables (Beyene et al, 2018). The concept is also called energy-from-waste (EfW) (Eleftheriou, 2002)

Local authority- refers to the designated authority governing a city, town or rural district council as defined in the Urban Councils Act section 29:15 (GOZ, 1995). In this research Harare City Council, Chitungwiza Municipality and Epworth Local Board are the three local authorities in the study area.

Harare province is the metropolitan area housing the three urban local authorities

1.2. Statement of problem

Municipal solid waste characterization for energy is an essential aspect of waste to energy management. While studies of this nature have been done in many parts of the world, it is extremely important to note that the characteristics of MSW for any two places will always be different due to differences in consumption patterns, rates of waste recovery and recycling, climatic conditions (affecting such parameters as moisture content) and the prevailing policy on waste management (World Bank, 2012). Even within the same geographical location, the waste characteristics are not static. They will evolve with changes in level of affluence and respective consumption patterns of that locality (UNEP, 2010)

Results of studies performed in one area can therefore be hardly generalized to recommend solutions in another area. Research recommends each area to perform its own assessment and design solutions compatible with its specific geo-climatic, economic and social characteristics. Couth & Trois, (2012); Lemaire et al., (2015) analysed the waste problem in Africa urban areas in separate studies and recommended various solutions. Lemaire et al., (2015), Gu Binxian et al., (2015) recommended that, ‘each municipality should assess its own challenges and potentials and develop the best mix of management options’. Similar studies have been done in many parts of the world for example, in Jordan by Abu-Qudais & Hani-A, (1999), in Saudi Arabia by Ouda et al, (2016), in Malaysia by Fazeli et al., (2016), in Nigeria by Nwankwo & Amah, (2016), in Kuwait by Al-Jarallah & Aleisa, (2014) and in Australia by Hla & Roberts, (2015). The common objective of these studies was to characterise MSW generated from a particular area and formulate appropriate WtE management options applicable to that area.

It is against this background that the present study was conducted. Because of the specific problems peculiar to Harare metropolitan province, in particular the low waste recycling rate, the severe proliferation of litter and the extremely low collection of refuse, the province urgently requires management options that drastically reduce the waste volume in order to restore the local authorities’ ability to handle incoming waste volumes. Tsiko & Togarepi, (2012) concluded that Harare’s waste problem seems to have no immediate solution. It is in view of the present study therefore that an integrated waste management approach inclusive of WtE conversion of a significant portion of the MSW stream can assure relief for the struggling local authorities.

1.3. Research objectives

The main purpose of the present study was to characterize the waste generated in Harare metropolitan province in the context of its value as a potential renewable energy resource. The specific objectives of this research are as follows.

1) To characterise the MSW stream in Harare metropolitan province in terms of physical and chemical properties for waste-to-energy management.
2) To evaluate the sustainable waste-to-energy management options for the MSW in Harare metropolitan province.

1.4. Research questions

1) What are the physical and chemical characteristics of municipal solid waste generated in Harare metropolitan province?
2) What potential exists in Harare metropolitan province for waste reduction (minimization), recycling and re-use in energy recovery?
3) What is the most sustainable waste-to-energy management option for the MSW in Harare metropolitan province?

1.5. Expected outcomes

1) Development of a basis upon which sound waste to energy management strategies for case-by-case analysis of urban areas can be made.
2) Making available empirical data on the MSW physical and thermochemical characteristics in Harare metropolitan province for future planning and decision making.
3) Publishing articles in peer review journals.

1.6. Research scope

The present study is confined to an assessment of the MSW generated in Harare metropolitan province, Zimbabwe as managed by Harare City Council, Chitungwiza Municipality and Epworth Local Board. Parameters of study are restricted to MSW quantities, composition, thermochemical characteristics and energy content. The study focusses on the characteristics of the waste based on an assessment between May to August 2017 and a scenario analysis over a 10 year period from 2017 to 2027.

1.7. Research significance

Recommendation for best practice in waste to energy management requires robust data for quantities of the MSW stream, its composition as well as its calorific value. Open dumping of waste leads to pollution and even well-managed landfills are a source of pollution especially if located to water sources (Beyene et al., 2018; Hla & Roberts, 2015). While waste prevention, reduction, recycling and reuse remain the most environmentally friendly waste management practices in terms of the waste management hierarchy (US EPA, 2016), history has proved their inadequacy in managing the increasing volume of MSW (Michaels, 2014). Poorly-planned waste to energy projects start on a very weak point and soon grind to a halt (Bag, Mondal, & Dubey, 2016). Often, personal interest and political correctness in decision making take precedence over practical judgement and ultimately leads to project failure (Abhishek Kumar et al., 2017). The current study contributes to reduction of risk of failure for waste to energy projects by examining the current MSW characteristics in the context of applicable WtE methods. Material flow analysis is a powerful tool for assessment the effectiveness of environmental systems and its applicability in sustainable waste management has been proven by many authors (Bergeron, 2016; Turner, Williams, & Kemp, 2016; Yahom, Malakul, & Charoensaeng, 2016).

At the local level, this study is useful to Harare metropolitan province by providing for the first time, data on the thermochemical properties of the MSW. The study compliments the country-wide baseline survey which was performed in 2011 in which an intensive solid waste characterization was performed. Additionally, the study translates into action some of the most important strategies outlined in the government of Zimbabwe ISWMP by providing data necessary for the design of municipal solid WtE programs. The plan, formulated in 2014, outlined the need to explore mechanisms to divert significant proportions of solid waste for energy recovery (GOZ, 2014).

Waste to energy recovery plans enshrined in Harare's 2012-2025 Strategic Plan (Harare City Council, 2012) as well as the country's Integrated Solid Waste Management Plan (2014) and renewable energy objectives of the ZIMASSET (GOZ, 2013) are unachievable without scientific data to inform decision making. WtE projects are generally capital intensive and so is designing and construction of modern-type landfills with engineering facilities for both leachate collection and LFG capture (Howes & Warren, 2013; Duffy, 2005). Choosing among options is only meaningful when data is available to buttress argument. An assessment of the thermochemical properties of MSW provides information on its self-combustibility in the absence of supplementary fuel (Komilis, Kissas, & Symeonidis, 2014; World Bank, 1999). The World Bank (1999) generally recommends that minimum combustible MSW fraction ideal for incineration with energy recovery should be 50,000 tonnes per year with energy content of no less than 6 MJ/kg at any time (World Bank, 1999). To enable the formulation of waste management strategies that can improve Harare province's waste management system, data on all these aspects had been missing, a gap which the current study sought to close.

CHAPTER 2

LITERATURE REVIEW

2.1 Global trend in solid waste generation and management

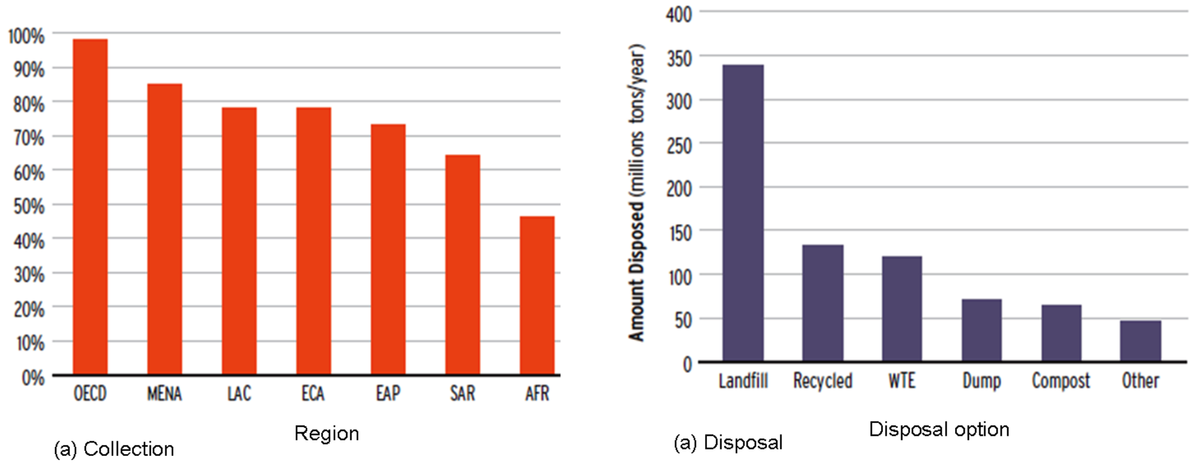
As at 2012, the World Bank reported that 1.3 billion tonnes of MSW were generated globally each year (World Bank, 2012). The largest contributors have been the high-income countries, particularly OECD countries with an average per capita MSW generation of 2.2 kg/day (Table 2.1). African countries contribute less than 10% of the global waste volume but despite so, waste management in most African countries is poor (Scarlat et al, 2015; Couth & Trois, 2010). It is estimated that by 2025, MSW volumes generated globally will reach 6.1 million tonnes per day (World Bank, 2012). The global mean MSW composition as reported by the World Bank (2012) is 46% organic, 17% paper, 10% plastic,5% glass, 4% metal and 18% other waste (World Bank, 2012). Waste collection is tied closely to income and ranges from 41% in low income countries to 98% in high income countries. In most industrialized countries increased waste diversion and recycling reduces the overall waste collection burden from municipalities, while the opposite is true for most developing countries, where waste collection alone consumes 80-90% of the waste management budget for municipalities (Couth & Trois, 2010). Landfilling remains the most dominant means of waste disposal globally (World Bank, 2012). Most low income countries however dispose of their waste in unprotected open dumps which become sources of perennial pollution and LFG emissions (Fig 2.1) (Couth & Trois, 2010).

Table 2.1 Global MSW generation by region

Region	Waste generation (kg/capita/day)		
	Lower boundary	Upper boundary	Average
Africa	0.09	3.0	0.65

Region	Waste generation (kg/capita/day)		
	Lower boundary	Upper boundary	Average
EAP	0.44	4.3	0.95
ECA	0.29	2.1	1.1
LAC	0.11	5.5	1.1
MENA	016	5.7	1.1
OECD	1.10	3.7	2.2
SAR	0.12	5.1	0.45

Source: World Bank, (2012).



(a) Collection

(a) Disposal

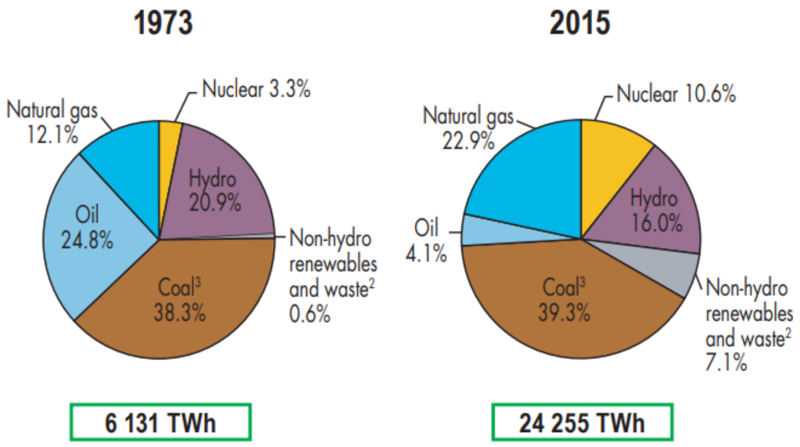
Fig. 2.1 Global overview of MSW collection and disposal.

Source: World Bank, (2012).

2.2 Global trend in energy production and consumption

Global concerns around energy security have initiated the need to both expand supplies and improve end use efficiency. In 2017 there was a shift in the fuel mix from coal to lower carbon fuels (BP, 2017). Even that is so, 80% of the primary energy supply is still dominated by fossil fuel (IEA, 2017). The global energy problem is not only the non-renewability of fossil fuels but also the impact of their extraction, transmission and subsequent use on the environment (IEA, 2016). Hence the need to adjust the energy mix to include more renewable sources remains urgent.

Unfortunately, while the global electricity generation has almost tripled over the past 50 years from 6,131 TWh in the 1970s to 24, 255TWh (IEA, 2017), the energy generation has expanded with a subsequent increase in utilization of fossil fuels (Fig. 2.2). Among the renewable and alternative energy options today are the various technologies for energy recovery from waste including incineration, pyrolysis, gasification, landfill gas capture, anaerobic digestion and refuse derived fuels (Beyene et al., 2018). Renewable energy is that which is replaceable in man's average lifetime while alternative energy refers to that which is adopted in replacement of fossil fuels (Tester, et al, 2012). In view of the current global energy situation, even though WtE is primarily focussed on waste management, the additional benefit of energy recovery is an important contribution to the renewable energy share.



1. Excludes electricity generation from pumped storage.
2. Includes geothermal, solar, wind, tide/wave/ocean, biofuels, waste, heat and other.
3. In these graphs, peat and oil shale are aggregated with coal.

Fig. 2.2 1973 and 2015 fuel shares of electricity generation

[1] excludes electricity generated from pumped storage; [2] includes geothermal (solar, wind, heat etc.); [3] in these graphs, peat and oil shale are aggregated with coal

Source: IEA, (2017)

2.3 History and global trend in energy recovery from waste

Energy recovery from waste evolved from concerns around poor waste management rather than the energy problem. In effort to solve problems arising from the growing volumes of waste, the mere mass burn incinerators of the late 19th centuries evolved into the modern materials resource recovery and waste treatment plants available today. Initial processes had no energy recovery objectives at all but today, the approach is not only to manage the waste and recover energy, but also to achieve economic gains from the entire system. Modern waste management has three main objectives: To protect the public and the environment, to save resources, energy and space as well as to dispose the residual wastes in such a way that they will not need treatment afterwards (Brunner & Rechberger, 2015). The scope of sustainable waste management is magnified from mere public health and environmental obligations to ensuring future generations will not bear the burdens of today's waste management approaches.

By March 1980, at least 21 operational WtE plants had been set up in the US (US EIS, 1980). Today, more than 1,200 WtE facilities exist in the US with capacity to process 31 million tonnes of MSW into energy. China now has the largest MSW incineration capacity (Lu, Zhang, Hai, & Lei, 2017). Denmark and Japan seem to be the global leaders in the WtE industry in overall with 67% of 65 million tonnes of MSW generated in Japan is treated thermally. By 2013, Japan had 1,172 plants with capacity to process 182 683 tonnes per day of MSW (Lu et al., 2017). Of these, 778 plants make use of residual heat while 328 plants have CHP generating a total of 1.8GW of electricity. 84% of MSW thermal power plants in Japan use the moving grate technology. By 2010, Europe had more than 452 operational WtE plants with capacity to treat both MSW and hazardous waste amounting to an estimated 73.4 million tonnes per year. By 2014, the UK alone incinerated 35% (6.72 million tonnes) of its total MSW stream generating 3.94 TWh of electricity (representing 1.1% of UK's overall energy supply by 2014) (TOLVIK Consulting, 2017). Emerging economies such as India, Thailand and South Africa also have a significant number of MSW to energy plants (Cheng & Hu, 2010).

2.4 Energy recovery from waste in Africa

While, energy recovery from waste has proved to be a viable option for managing solid waste with the additional benefit of energy recovery in many industrialized for more than 50 years, the technology is still either poorly understood or failing to gain momentum in many African countries. Studies conducted suggest that the cost of most thermal based technologies especially incineration, as well as their technical expertise requirements could be the one pushing energy recovery from waste beyond the reach of most countries in Africa (Couth & Trois, 2012; Scarlat et al., 2015; Lemaire et al., 2015). As a result, not so many WtE plants exist in Africa in comparison with Europe, Asia or the US. A couple of LFG to electricity plants have been installed in Mauritius, South Africa and Algeria while the first WtE thermal plant is under construction in Ethiopia (WEC, 2016). Namibia has an RDF plant which is providing fuel for co-generation in cement kilns (CEMNET, 2017). Several feasibility studies have been conducted, yet too few have been implemented. Table 2.2 shows a list of 10 studies that have been conducted in Africa and the results.

Table 2.2 A list of 10 selected studies related to WtE in Africa

Country, City	Year	Focus of study and findings	Remarks	References
South Africa, Durban	2017	Study explored opportunities and challenges for growing South Africa's WtE industry. Increasing landfill costs, inclusion of WtE in the electricity generation roadmap, and availing appropriate government subsidies were identified as some of the enablers	The first LFG to electricity was installed for Ethekwini Municipality in Durban and through the study South Africa seeks to increase the WtE capacity	(City Energy, 2018)

Country, City	Year	Focus of study and findings	Remarks	References
Ethiopia, Addis Ababa	2017	MSWI with energy recovery; The energy content was reported to be 12MJ/kg; It was not specified however whether the value represented LHV or HHV	The findings may lead to Africa's first MSWI plant; No scholarly publication of the study results is available	(WEC, 2016)
Zimbabwe, Bulawayo	2016	A pre-feasibility study showed that setting up a WtE plant in Bulawayo would cost approximately US$68 million, and the plant can produce 110 000 litres of bio-diesel and 2,2 MW of electricity	There is no scholarly publication of the study results. The project has not yet materialized;	(Nyoni, 2016)
Mauritius, City not specified	2015	Opportunities for creating a sustainable economy through innovations in various sectors including waste management. LFG can be recovered from 75 000 tonnes of organic waste landfilled in Mauritius to produce 0.07KWh of electricity per m^3 of LFG.	Through research and promotion, Mauritius installed a 3.3 MW LFG to electricity plant which is now operational since 2011. The study reported here was aimed at capacity optimisation	(PAGE, 2015)
Several countries	2015	An assessment of the potential for energy generation from African cities showed that 122.2TWh can be generated under optimal MSW collection	Study was limited due to unavailability of country-specific data. Since then adoption of WtE is still very poor in Africa	(Scarlat et al., 2015)
Ghana, cities not specified	2013	Prospects of electricity generation from MSW were explored. Landfilling with LFG recovery and utilization was compared with landfilling without LFG utilization and controlled incineration. LFG to electricity was concluded to be the cheapest alternative (US$0.039/KWh) and capable of producing between 1—2 MW of electricity	A scholarly publication is available for the study; Several pre-feasibility studies have been conducted but no WtE projects have been installed to date	(Ofori-Boateng, Lee, & Mensah, 2013)

Country, City	Year	Focus of study and findings	Remarks	References
Nigeria (Lagos and Nsukha)	2013	The study explored the potential of electrical power generation from MSW and showed that a combined heat and power (CHP) plant can generate electricity that can sell in Lagos and Nsukha at prices comparable to that of the conventional sources	A scholarly publication is available for the study; Several pre-feasibility studies have been conducted but no WtE thermal power projects have been implemented in Nigeria to date	(Amoo & Fagbenle, 2013)
Cameroon, Yaounde	2012, 2011	Climate advantages related to the use of MSW as a source of energy in Cameroon. In 2011 a report indicated the Cameroon government was targeting to install a 100MW WtE power plant	No scholarly publication is available. The project specifications were not provided. No WtE project has been installed in Cameroon to date	(Emmanuel, 2011)
Ghana, Kumasi	2009	MSW incineration, LFG to electricity and AD were compared in terms of electrical energy output and environmental emissions through a modelling in MATLAB, Simulink. Incineration resulted in the highest energy yield (191 000MWh/yr.) but with the highest level of pollution (114 000 ton/year of CO_2 eq.)	A scholarly publication is available for the study; Several pre-feasibility studies have been conducted but no WtE projects have been installed to date	(Rajaeifar et al., 2017)
Tanzania, Dar-es-Salaam	2004	Electricity generation from MSW through AD was investigated. The MSW characterization study revealed that the MSW has a high organic content from which approximately 1 900 MWh/year of electricity can be generated. A more recent study was reported but the publication is not reputable hence it has not been included in the current summary.	Even though the study was conducted close to one and half decades ago, no WtE project has been installed in Dar-es-Salaam to date	(Mbuligwe & Kassenga, 2004)

2.5 Overview of waste generation and management in Zimbabwe

With a 2016 population estimated at 14 million (projected to grow to 17 million by 2025), Zimbabwe's waste generation was estimated at 1.8 million tonnes (ZNSA, 2017). Harare province houses 49.6% of the urban population and is the worst affected by poor waste management. The MSW composition mirrors that of most developing countries in having high proportion of organic waste (Fig. 2.3) Waste collection in Zimbabwe's urban areas fails to meet the minimum environmental protection standards. In 2011, waste collection by responsible local authorities was below 30%, the recycling rate was estimated at only 2% (Tsiko & Togarepi, 2012) and the unsustainable waste and wastewater disposal practices are believed to have contributed to periodical cholera and typhoid outbreaks over the past one and half decades (Watyoka, 2016).

Of the 1.65 million tonnes of solid waste generated in the urban areas in 2011, 28% was burned at source, 11% burned, 6% dumped in undesignated spaces, 3% recovered while 52% was collected for formal disposal (IES, 2013). Harare, which is the most densely populated city in Zimbabwe, uses unprotected dumps for the disposal of refuse. Refuse burning and unauthorized scavenging are common practices at Harare and Chitungwiza refuse dumps both of which lack mechanisms to prevent leachate from infiltrating into the ground. LFG recovery remains a component in the pipeline for all local authorities in Zimbabwe. WtE plants in Zimbabwe have mainly been in the form of isolated small-scale biogas plants utilizing mostly livestock manure but effort to utilize MSW had not been explored.

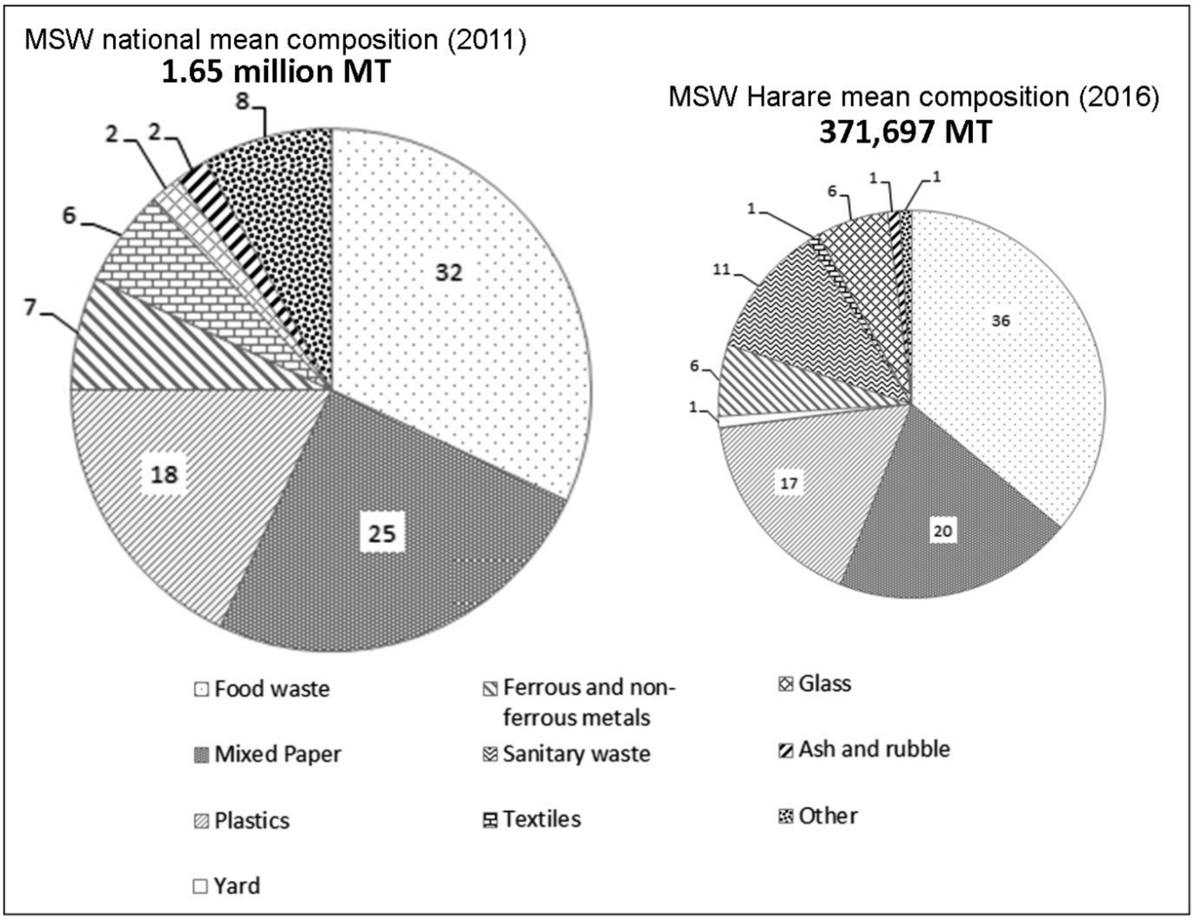


Fig. 2.3 MSW composition data for Zimbabwe, national mean (2011) and Harare (2016)

Data sources: [2011]:-(GOZ, 2014); [2016]:-(EMA, 2016)

2.6 Zimbabwe's new integrated solid waste management plan

In an attempt to solve waste management problems, the government announced a new plan in July 2014 (GOZ, 2014). The new integrated solid waste management plan (ISWMP) attempts to solve the waste management problem in Zimbabwe by taking an exhaustive approach on the waste management hierarchy (US EPA, 2016). The plan has 6 aspects and 10 goals which spell out the strategies aimed at waste prevention, waste reduction, waste reuse, recycling, energy and materials recovery and safe disposal (GOZ, 2014). The plan identifies communities, corporations, government ministries and agencies and private players as important stakeholders in waste management. Data to support the implementation of the plan is scarce in Zimbabwe and most intervention actions are not designed on the basis of empirical evidence. Research in waste management has also been highlighted as an important strategy in order to provide decision makers with reliable data to support the implementation of the ISWMP

2.7 Zimbabwe's legislation governing solid waste management

The Environmental Management Act Chapter 20:27 (EMA, CAP 20:27) is the principal law governing environmental issues in Zimbabwe (EMA, 2016;EMA, 2017a). It is enforced primarily by the Environmental Management Agency (EMA) with the aid of other policing agents including the Zimbabwe Republic Police. Additionally, the government passed statutory instrument 6 of 2007 (officially read as Environmental Management (Effluent and Solid Waste Disposal) Regulations, 2007) in order to expand the provisions of EMA, CAP 20:27. The statutory instrument prescribes lawful practice regarding collection and disposal of solid and liquid wastes. For instance disposal of waste at places other than those registered as landfills is illegal and so is littering. SI 6 of 2007 set up to December 31, 2012 as the deadline for all urban and rural local authorities to have replaced unprotected dumps with engineered sanitary landfills, a deadline which none of the local authorities met. Open burning of waste and open dumping of waste is also prohibited.

Organizations discharging wastes into any part of the environment must do so under a license issued by EMA. The licensing system is based upon the polluter pays principle with stiffer fees and penalties for wastes causing higher levels of pollution (EMA, 2017a). The legal framework regarding waste management is indeed sound yet the enforcement is rather poor due to other factors including a weak economy that make it difficult for municipalities to comply and upscale their waste management infrastructure in line with the prevailing policy. Additionally, the law still emphasizes the traditional collection and disposal approach to waste management and does not give clear command regarding resource recovery, including energy recovery. The ISWMP spelt out a new direction for waste management. EMA CAP 20:27 is yet to be amended in order to tie its emphasis with the new policy.

2.8 Energy recovery from waste technologies

Modern waste treatment technologies are divided into biochemical and thermochemical processes. Biochemical processes include composting, anaerobic digestion, fermentation, and landfill gas to electricity. Thermochemical waste treatment technologies include incineration (MSWI) or mass-burn, gasification, pyrolysis and refuse derived fuel. Transesterification is a less common physicochemical conversion technology which converts MSW into a liquid fuel (biodiesel). Except for composting, the bulk of modern waste treatment technologies result in recovery of fuels and energy in the form of biogas, heat, syngas, ethanol, biochar, pyrolysis oil and electricity (Malinauskaite et al., 2017).

The conventional WtE systems have been in operation since the turn of the 20th century and are considered mature technologies. MSWI, anaerobic digestion (MSW bio-digesters), LFG to electricity, gasification and RDF commercialization is widespread in many industrialized countries including the US, EU and selected Asian countries (WEC, 2016). Fig 2.4 is a schematic of the major WtE technologies, processes involved, the products and respective applications.

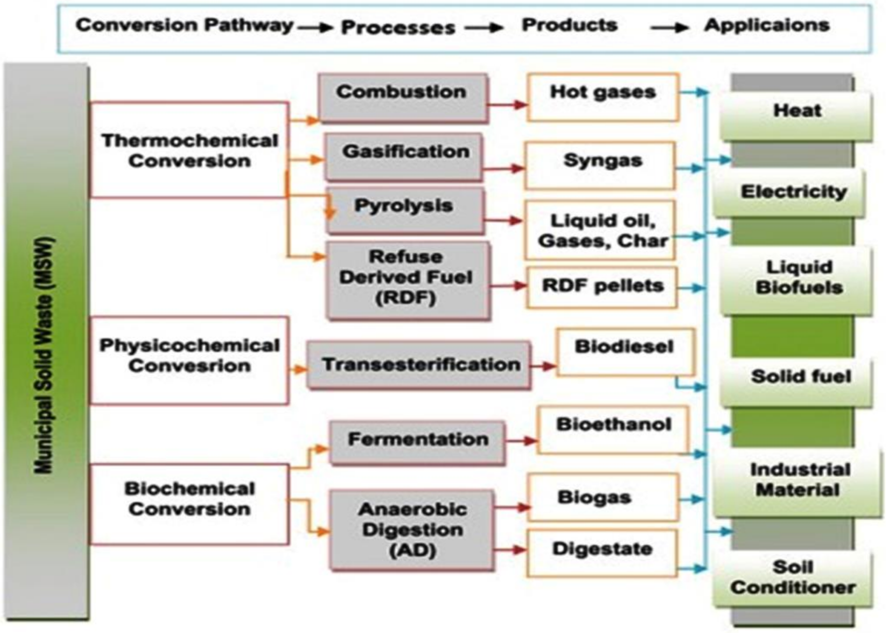


Fig. 2.4 Major WtE technologies, processes, products, and applications

Source: (Malinauskaite et al., 2017)

2.8.1 Anaerobic digestion (AD) with biogas and digestate utilization

By definition, anaerobic digestion (AD) is a process in which complex organic molecules are broken into simpler compounds by microbes using exo-enzymes in the absence of oxygen (Vanapruk, 2017; Monnet, 2003). The polymers of carbohydrates, lipids and proteins are converted into simpler monomers and subsequently into biogas by methanogenic bacteria. The process can be broken into four sub-processes (Fig 2.4). These are hydrolysis, acidogenesis, acetogenesis and methanogenesis.

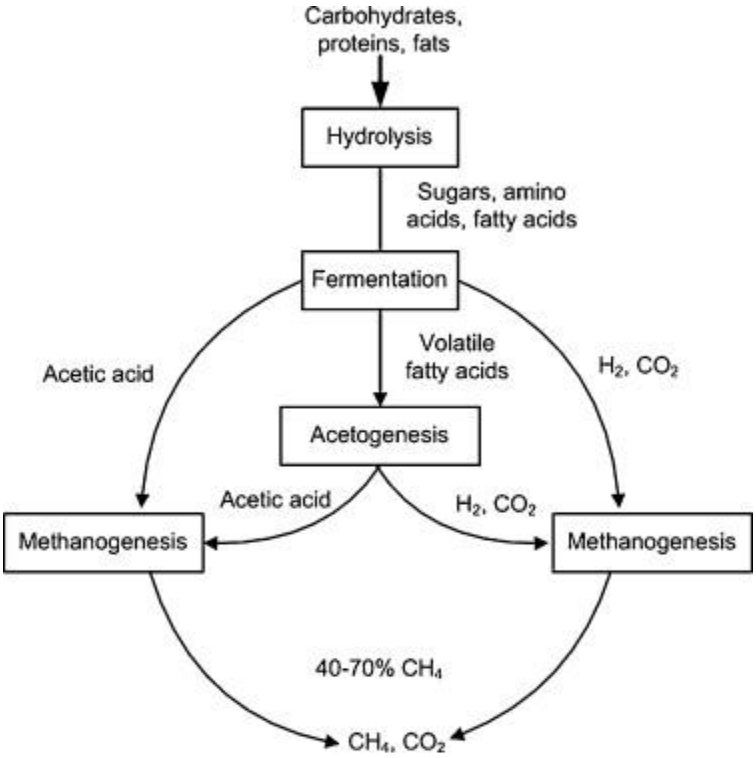


Fig. 2.5 Schematic of the anaerobic digestion process

Source: Lou, Nair, & Ho, (2012)

(i) Hydrolysis

During hydrolysis, complex carbon macromolecules that constitute living matter are broken down into their monomers which include soluble sugars, amino acids and long chain fatty acids. The process is catalysed by extra-cellular enzymes such as amylase, cellulose and lipase.

(ii) Acidogenesis

During acidogenesis, the products of hydrolysis are converted into organic acids (mainly volatile fatty acids) hydrogen and carbon dioxide. The process is facilitated by acidogenic bacteria. The process greatly lowers the pH of the reactor and this fact is an important aspect that must be taken into consideration in system designs.

(iii)Acetogenesis

This process involves conversion of products of acidogenesis mainly volatile fatty acids (VFA) into acetate (CH_3COOH). Various microbes are involved, some of which convert higher VFAs into acetate, hydrogen and CO_2 while others convert hydrogen and CO_2 into acetate. Hence the main product of this stage is acetate.

(iv) Methanogenesis

Methanogenic bacteria form methane mostly by splitting acetate. 70% of the methane is formed this way. Other bacteria reduce carbon dioxide using hydrogen. The result is biogas which comprises of 55-75% methane, 30-45% CO_2 and traces of hydrogen sulphide, nitrogen, hydrogen and other gases (Table 2.3)

Table 2.3 Composition of biogas

Constituent	Composition
Methane (CH_4)	55-75%
Carbon dioxide (CO_2)	30-45%
Hydrogen sulphide (H_2S)	1-2%
Nitrogen (N_2)	0-1%
Hydrogen (H_2)	0-1%
Carbon monoxide (CO)	Traces
Oxygen (O_2)	Traces

Source: Hilkiah et al., (2008)

For MSW, AD is done in specialized bioreactors designed to handle the OFMSW. Some are wet systems while others are dry systems. Some operate in batches (batch systems) while others work with plug-flow systems (continuous anaerobic digesters) (Rapport, Zhang, Jenkins, & Williams, 2008). The recovered methane can be used directly as a primary heating fuel or it can be upgraded and used in gas engines to produce mechanical power (Brown, 2011). Hence it can be used in electricity production with about 40-42% fuel to power efficiency (Beyene et al., 2018). The residue of AD is a compost-like digestate which can be re-circulated into the AD system to improve efficiency (Michele, Giuliana, Carlo, Sergio, & Fabrizio, 2015). After complete use, the digestate is usable as a soil conditioner (Li, Park, &

Zhu, 2011). A more detailed review on AD technologies and current practices is available in a review made for EMA Zimbabwe, titled, "*Municipal solid waste anaerobic digester designs: A review to support decision making for Harare metropolitan province*" An abstract is presented in Appendix E

2.8.2 Landfill gas (LFG) to electricity

LFG to electricity takes advantage of decomposing waste in an engineered sanitary landfill to collect and use methane (CH_4) present in LFG to produce electricity by direct combustion in gas engines with approximately 40-42% fuel to power efficiency (Silva, Barros, Tiago Filho, & dos Santos, 2017). Methane concentration in landfill gas depends primarily on the organic fraction of municipal solid waste (OFMSW) present in landfilled wastes and may range between 50-55% with the remainder being CO_2 and other non-methane organic compound (NMOC) (ATSDR, 2017). OFMSW in the waste is broken down under anaerobic conditions in a similar way to AD albeit with lower efficiencies since AD is a controlled process. Up to four (4) phases can be identified concerning OFMSW decomposition in landfills with the highest methane output in the 3rd and 4th phases, which normally occur after at least 1 year of waste acceptance (Fig 2.6). For typical LFG to electricity installations, the methane recovery efficiency is approximately 70% (Silva et al., 2017). Since landfilling is the most common method of waste disposal, it follows that LFG to electricity is the least expensive WtE technology where an engineered sanitary landfill already exists. However, land requirement for construction of new landfills has made it an unattractive choice in countries where land is scarce and expensive, such as the EU (Malinauskaite et al., 2017)

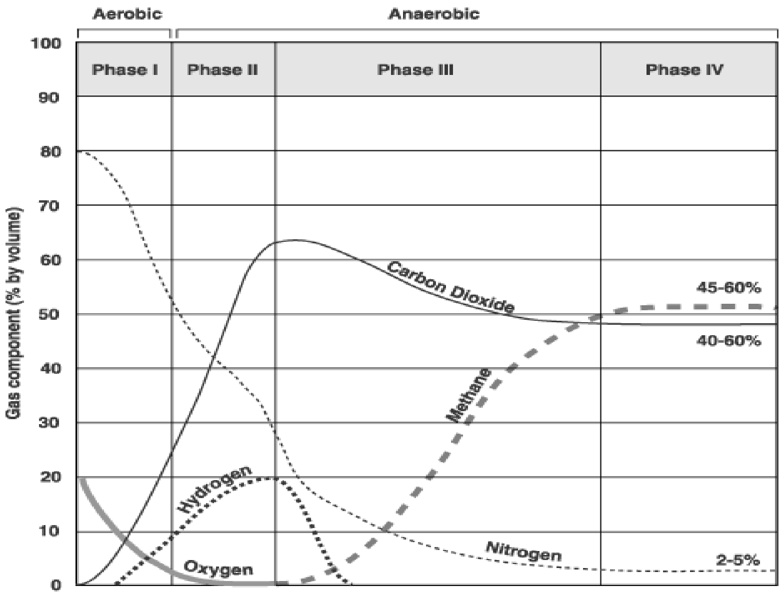


Fig. 2.6 LFG production profiles in a typical landfill

Source: ATSDR, (2017)

2.8.3 Municipal solid waste incineration (MSWI) and other thermal WtE

Thermal based technologies make use of high temperatures and in some cases high pressure to re-arrange the majority of carbon atoms in waste constituents into valuable products. The technologies include MSWI, pyrolysis, gasification and hydrothermal carbonization (Brown, 2011; Staley, 2013). Table 2.4 gives an overview of these processes.

Table 2.4 Thermal WtE processes

Comparison basis	Incineration	Gasification	Pyrolysis	Hydrothermal carbonization
Feedstock[1]	Full mix of MSW less bulky items, and chlorine containing materials	Mixed MSW less glass, metal, inerts and contaminants	Mixed MSW less glass, metal, inerts and contaminants	Mixed MSW less glass, metal, inerts, contaminants
Moisture content limits	Less than 30%	Less than 10%	Less than 20%	More than 70%

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[1] In theory, food waste can be treated thermally but its high moisture significantly lowers the heating value so for these processes food waste may be removed

Comparison basis	Incineration	Gasification	Pyrolysis	Hydrothermal carbonization
Oxidation level	Complete oxidation	Partial oxidation	No oxidation	No oxidation
Process type	Exothermic	Endothermic/exothermic	Endothermic	Endothermic
Temperature	470-1200°C	788-1650°C	400-900°C	Above 1000°C
Main products	Heat, electricity	Syngas, ash/slag	Biochar, pyrolysis oil, some syngas	biochar

Source: Adapted with modifications from Staley, (2013) and Velzy & Grillo, (2007)

These WtE technologies offer a great advantage in treating municipal solid wastes and especially where landfill space is both scarce and expensive, they serve as the best alternative to landfilling. They are preferred because of the high versatility of the conversion pathways involved and products generated. Of them all, MSWI is by far the most common and well proven thermal WtE technology (Beyene et al., 2018). It can reduce the MSW volume by 90% and mass by 70% while producing heat that can be used to generate electricity in a Rankine cycle (Brown, 2011). Moving grate incinerators and fluidised bed incinerators are the two main types of incineration technologies employed for MSW direct combustion. Moving grate types are the most common types with over 90% of MSW incinerators in Europe employing moving grate technology (Lew, 2016). Their advantage over fluidized bed incinerators is that they require no prior sorting or separation of MSW materials, accommodate large quantities of MSW up to 4,300 tonnes/day and they can operate well with MSW of fluctuating heating value. Heat produced from incineration of MSW can be used to generate steam and electricity in a CHP plant.

Energy requirements for incineration plants range between 21 KWh to 93.5 KWh per tonne of feedstock processed while electricity energy outputs are in the range of 400 KWh to

700KWh per tonne of MSW although these estimates vary widely with characteristics of feedstock (Beyene et al., 2018). Efficiencies for a CHP plant can be as high around 20-22% (Beyene et al., 2018). These authors all concur on the huge variability in combustibility of MSW as a feedstock for thermochemical conversion. Energy content on a dry basis ranges between 8—13 MJ/kg (Zhou et. al, 2015). The general recommendation for MSW thermochemical conversion is that throughout all seasons, the energy content of the MSW should not be less than 6MJ/kg especially for mass-burn incineration (World Bank, 1999). Authors World Bank, 1999, Tester et al., 2012 agree that the unpredictability of MSW characteristics as a feedstock primarily due to its heterogeneity is among the prime concerns in the performance of WtE systems.

A more detailed review of MSWI is presented in the paper, *"The evolution of waste to energy incineration: A review"* which at the time of writing is at revision review stage in Renewable and Sustainable Energy Reviews journal. An abstract is presented in Appendix E.

2.8.4 RDF for electricity co-generation with conventional fuels

Materials Recovery Facilities (MRFs) are dedicated systems for the recovery of recyclable materials from the MSW stream. When ferrous and non-ferrous metals, glass, rubble, ash and other incombustibles are removed, the residue can be densified into refuse derived fuels (RDF) (Malinauskaite et al., 2017). In some cases, food wastes and other high-moisture containing organic wastes are removed prior to the densification process (Staley, 2013). The product, RDF is often preferred over unprocessed MSW due to its higher energy content, lower moisture content and better storage and transportation characteristics (Chang, Chen, & Chang, 1998).

The lower heating value of RDF may be as high as 22 MJ/kg due to the presence of plastic waste which may have a lower heating value as high as 40 MJ/kg (Zhou et. al, 2015; Lombardi, Carnevale, & Corti, 2015). The use of RDF in electricity co-generation especially in coal power plants is a common practice in many countries (Beyene et al., 2018; Lu et al., 2017). Since WtE is considered a carbon-neutral technology, the objective is to reduce net CO_2 emissions by replacing a portion of coal that would have otherwise been used in the conventional power plant. The major drawback is related to combustion problems in systems that were not primarily designed for co-generation (Chyang et al., 2010). In particular, because of the heterogeneous nature of MSW, more sophisticated flue gas treatment systems are necessary for co-generation plants in comparison to systems utilizing coal or biomass alone (Edo et al., 2017)

2.8.5 Hybrid technology (AD+ MSWI)

Hybrid plants are installed where the MSW throughput is often too large to be handled by standalone installations hence the need to bring together complementing technologies in order to create synergies and optimize efficiency (Brown, 2011). They are less common due to the overall investment and operational costs which may make it difficult for installations to operate with economic viability (Beyene et al., 2018). In the current study, the hybrid plant considered involves AD and incineration with energy recovery.

2.8.6 WtE technology capital expenditure (CAPEX) and operational expenditure (OPEX)

WtE technologies are in overall more capital intensive ventures when compared to landfilling which is the one of the reasons for their slow adoption in counties where land for constructing sanitary landfills is vast and inexpensive (Scarlat et al., 2015). Fig 2.7 shows the major WtE projects aspects for which CAPEX and OPEX consideration must be made. Due to lack of experience in the region where the current study was conducted, no appropriate typical CAPEX and OPEX values could be cited. Table 2.5 shows typical CAPEX and OPEX values for MSW treatment technologies based on a 2017 study in Asia. Therefore, for reference and comparison purposes in the current study, typical values reviewed in this section are used.

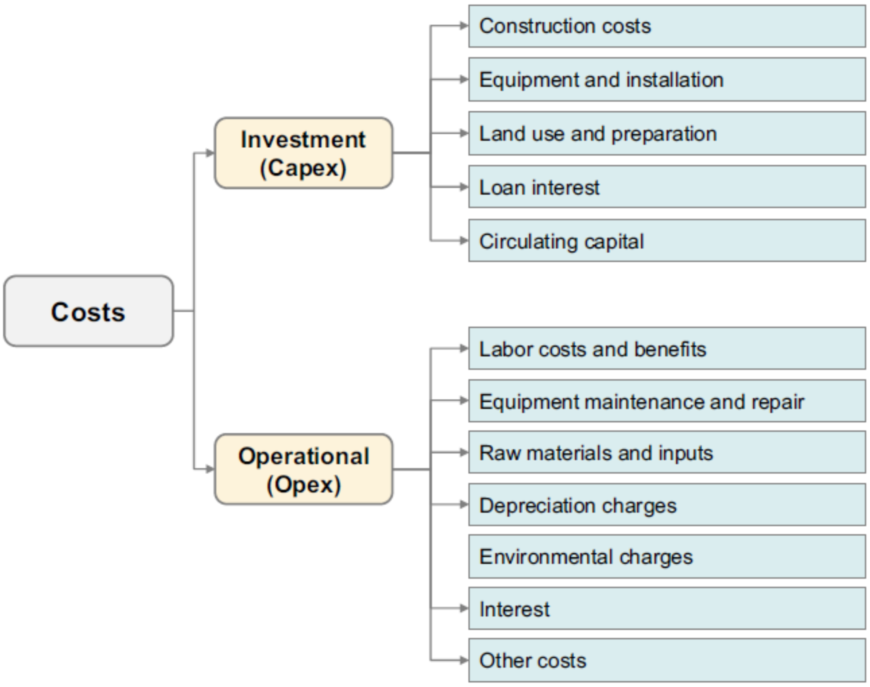

Fig. 2.7 CAPEX and OPEX for WtE facilities

Source: Aleluia & Ferrão, (2017)

Table 2.5 Typical CAPEX and OPEX values WtE technologies

Technology	CAPEX (Million USD_{2015})		OPEX (USD_{2015}/ton of treatment capacity)	
	Range	Average	Range	Average
Composting	0-36	5	2.8-25.7	11.5
Anaerobic	0.002-31	4	6.9-25.9	15.2
MSWI	41-185	83	5.2-29.9	20.0
RDF	0.051-37	11	-	-

- Data not given. Data source: Based on a 2017 study in Asia from Aleluia & Ferrão, (2017)

2.8.7 De-merits of waste-to-energy technologies

Despite being highly useful as an alternative to MSW landfilling, waste to energy processes can have serious negative impacts. WtE has been viewed as indirectly promoting waste generation, hindering waste minimization and obstructing recycling efforts (Cheng & Hu, 2010). Waste incineration for example, remains a highly debatable option throughout the world because of the harmful properties of untreated flue gas. Without proper controls, municipal solid waste thermal treatment generates flue gases containing dioxins, polycyclic aromatic hydrocarbons (PAHs) which are a family of at least 75 chlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and poly-brominated compounds such as poly-brominated diethyl ethers (Cheng & Hu, 2010). These compounds are toxic, carcinogenic and known endocrine disruptors (Dearden, 2004). Additionally, they are hydrophobic (and hence lipophilic), stable and resistant to metabolism making them difficult to excrete from the body. This makes them bio-accumulative and essentially harmful to ecosystems (DioxinFacts.Org, 2017). They are present in waste, and even though they may be destroyed during combustion at high temperatures, they are capable of reforming in post combustion flue gases. They are highly persistent in the environment hence the term persistent organic pollutants (POPs) because of their long half-life which ranges from years to decades (Vane et al., 2014)

Modern incinerators are equipped with highly sophisticated engineering techniques for both flue gas quality monitoring and clean-up of flue gas before release into the atmosphere (Niessen, 2010). These include electrostatic precipitators (ESP) for PM control, acid gas or wet scrubbers, airbag filters and carbon filters. Flue gas treatment is a very expensive process and is usually what pushes the overall initial investment cost beyond the reach of many local authorities. Bottom ash making up 20-35% of MSW incineration waste by weight may contain traces of heavy metals. Fly ash and materials trapped in the flue gas treatment equipment contain toxic compounds and the resulting hazardous waste requires specialized handling and disposal. In some cases, the low heating value exhibited by MSW forces operators to co-incinerate with coal which may require modification of air control systems (Zhang, Huang, Xu, & Gong, 2015; Fruergaard & Astrup, 2011),

The large machinery requirement for WtE technologies may make overall cost of waste treatment very high. In some cases, equipment has very short lifespan because of corrosive properties of many waste components. For example, wet AD machinery lifespan can be as low as 3 years which pushes maintenance costs unbearably high and makes WtE businesses involving wet AD unprofitable (Vanapruk, 2017)

A summary of the description, applicability, merits and demerits of the five alternative WtE options considered in the current work (apart from the base case) are summarised in Table 2.6.

Table 2.6 Summary description, merits and de-merits of WtE technologies under current study

Option	General description	Applicability	Merits	De-merits
Landfill with LFG capture system	Landfilling is unarguably the most common method of MSW disposal. When coupled with LFG capture system, LFG which may contain up to 60% methane is collected for either direct use in local heating applications or used to power a gas engine which will be coupled to a turbine to produce electricity. In some cases the LFG is simply flared to reduce CH_4 to CO_2 which has a lower Greenhouse warming potential.	Unsorted waste can be landfilled. High organic waste content, high moisture content are all important for LFG generation	Mature technology, sanitary landfilling with leachate control and LFG capture minimise pollution of the environment. Lower CO_2 emissions, less expertise requirements in comparison to power plants and incinerators	LFG production sorely depends on bacterial activity in AD of landfilled waste which is often a slow process especially in cold and temperate climates; Requires large area which may be too expensive or unavailable in some countries
MSWI	Thermal treatment of MSW to produce heat and electricity. Combined heat and power (CHP) cycles offer better efficiency	Unsorted MSW can be incinerated. However, high moisture content	Mature technology; Capable of reducing landfill space requirements by over	High initial investment and operational costs; High emission of pollutants

Option	General description	Applicability	Merits	De-merits
	in comparison to simple power plants.	especially associated with high food waste content works negatively against combustion and lowers net energy output. MSW calorific value should be 6MJ/kg as minimum and feedstock availability at least 50,000 metric tonne/yr. (World Bank, 1999)	90%; Capable of producing additional heat and electricity to supplement traditional supplies; Extremely valuable option in areas where land for landfilling is scarce.	with potential dioxins, PCBs, PAHs, High technical expertise requirements; Incapable of treating 100% of MSW volume and still requires sanitary landfilling of residual waste and ash
AD with biogas and digestate utilization (Bio-digesters)	Anaerobic digestion (AD) of organic fraction of MSW in bio-digesters. Biogas which is 40-60% methane ((Brown, 2011) is produced. This can be further processed	Strictly the organic fraction of MSW stream	Mature technology; environmentally friendly during operation; less technical and expertise	Biogas output sorely depends on microbial activity and may be slow especially in cold and temperate climates;

Option	General description	Applicability	Merits	De-merits
	to improve quality through bio-filtration, de-sulfurization etc. and used directly in heating applications. In some cases it can be used to power a gas turbine for electricity generation		requirements in comparison to incineration; Biogas produced can be readily used for local heating or further cleaned and connected to natural gas pipeline	Still requires other options to deal with residual inorganic waste. Wet AD highly corrosive to equipment. Short equipment lifespan (around 3 years) makes overall operating costs very high; Biogas output from dry AD very low
RDF	Separation and mechanical processing of MSW into refuse derived fuels which can be used in boilers, cement kilns and other applications to replace fossil fuel or traditional biomass. Processing may include drying, shredding, crushing, mixing with binding chemicals and	Combustible fraction of MSW. Organic fraction containing high moisture levels make RDF processing more energy consuming and may be separated. Leachate can	Mature technology; Resulting RDF has higher calorific value in comparison to unprocessed MSW; RDF easier to store, handle or transport in comparison	High initial and operating costs as technology depends on expensive machinery and equipment; MSW with high moisture content increases operating costs; high energy requirements as the process is

Option	General description	Applicability	Merits	De-merits
	palletisation. The higher the level of processing the higher the cost of production. Fluffy RDF may be preferred to lower cost of RDF production	be squeezed off the MSW and preferably used as inoculum for AD in bio-digesters.	to raw MSW	usually highly mechanized which lowers net energy output
Hybrid	Hybrid system will combine two technologies so as to increase overall efficiency and maximise returns	Requirements will depend largely of the selected hybrid system	Mature technologies can be selected to complement each other and increase overall efficiency	High initial investment and operating costs; Increased technical and expertise requirements in comparison with single technologies

2.9 MSW characterization for energy recovery

Before considering MSW for WtE recovery, important data must be gathered on the physical and chemical characteristics of the waste including energy content. The quantities and flows of the MSW must be investigated. The strengths and limitation of the prevailing waste management system must be evaluated. The applicability of the various technologies reviewed above must be thoroughly evaluated before selection of the ideal option is done. In this section the various tools available for collecting this important information is reviewed.

2.9.1 Determination of mean MSW composition-quartering method

Physical determination of composition refers to an evaluation of the MSW stream from a given locality in terms of the major categories for example food waste, paper, plastics, rubber and so on. It also includes an evaluation of the moisture content as-discarded. Standard methods of determining physical composition should be applied. Standards are developed for the assessment and validation of research methods in order to eliminate bias and reduce personal subjectivity. A number of standard methods are available for the determination of the composition of unprocessed municipal solid waste. Among these is the widely accepted *quartering and coning method* developed as the standard test method for determination of the composition of unprocessed MSW by the American Society for Testing and Materials (ASTM) (ASTM, 2016; EPA, Ireland, 1996; Hla & Roberts, 2015).

2.9.2 Waste generation rate (WGR)

Waste generation rates and volume of MSW are important parameters as they give a quick indicator of the landfill lifespan and a general guide as to how much the urban local authority is faced with for collection, transportation and disposal. This is crucial in decision making, particularly for waste management resources allocation. MSW generation rates differ from one locality to another depending on many factors including level of standard of living or economic prosperity, seasons, prevailing policy or legislation governing waste recovery and recycling as well as public attitudes. In WtE management, waste generation rates point to the quantities of MSW available as feedstock to ensure the energy recovery plant will not require additional fuel (Panepinto & Zanetti, 2018)

Two methods exist for determining the WGR namely load count analysis or weight/volume analysis (Palanivel & Sulaiman, 2014) and material flow analysis (Brunner. & Rechberger, 2004). The methodology for weight/volume analysis is quite simple. For the chosen area of collection, the number of loads is recorded over time together with corresponding weight and volume of each vehicle. Modern landfills are equipped with weigh bridges for ease of measurements and the vehicle volumes are static functions which are used for the final volume determination. In dealing with a complex subject such as municipal waste management, WGR is usually an estimate.

$$\text{WGR} = \frac{\text{weight/volume of solid waste (tonnes or cubic metres)}}{\text{Time period } (t)} \qquad [2.1]$$

Usually, WGR will be expressed in tons per day or cubic metres per day. If the result is divided by the population of that specific area, the per capita WGR (Palanivel & Sulaiman, 2014) is computed

$$\text{Per capita WGR} = \frac{\text{WGR}}{\text{Population } (p)} \qquad [2.2]$$

The weakness of this method is that it neglects the waste collection rate (WCR) and works well where WCR approximates 100%. Unfortunately in many urban areas today, WCR is never 100%. If the WCR is known, computing WGR should take it into account. In which case:

$$\text{Ultimate WGR} = \frac{\text{Site determined WGR}}{\text{WCR}} \qquad [2.3]$$

If the WCR is not known, the WGR can be determined by material flow analysis. By setting up a system boundary, all activities that cross and occur within the boundary affecting WGR should be taken into account. This include the ‘sinks’ of uncollected MSW piling up in open spaces and any MSW stream that leaves or enters the boundary as export or import between the area chosen for study and other areas around it. The ultimate WGR is then reported after all the components of the MFA have been balanced. This is particularly important today where several management options are to be considered. MFA can assist in knowing the pathways taken by the MSW stream with a holistic and inclusive approach.

2.9.3 Bulk density

This parameter is useful in determining the extent to which the MSW can be compacted during storage, transportation and disposal. Modern garbage haulers are compacter trucks which have mechanisms to compact the refuse to optimize quantity of MSW carried at any given time. Landfilling also employs compaction as part of the refuse disposal system. The extent to which refuse will be compacted will depend on this vital aspect. Widely accepted method is the *mass per unit volume technique* (EPA, Ireland, 1996; Huerta-Pujol, et al., 2010). Other less common approaches make use of mechanical devices such as the oedometer used in soil compressibility assessments or pycnometer (Stoltz, Gourc, & Oxarango, 2010)

2.9.4 Proximate analysis

Proximate analysis involves laboratory examination of a sample of the MSW for moisture content (MC), volatile matter (VM), fixed carbon (FC) and ash, parameters of which are important in energy content estimation as well as the design of the combustion chamber for thermal-based energy recovery methods. Ideal methods for proximate analysis should be based on known standards such as ASTM E 1756-08 (for MC), ASTM E-872 (for VM), and ASTM D1102 (for ash). Fixed carbon is based on simple arithmetic calculation.

The moisture content as-discarded refers to the amount of water present in the MSW at the time of disposal. Moisture content in landfilled or openly discarded waste will fluctuate depending on a number of factors including climate, method of disposal (whether the waste will be compacted and covered or not) and the nature of the underlying material (affecting rates of leachate infiltration and/or percolating from the waste volume). MC determination is critical in WtE management as the various technologies require different MC levels as has been discussed before. This helps in determining the waste pre-treatment prior to the final energy recovery. At least 2260 KJ of energy is consumed in vaporizing each kilogram of water during combustion (Basu, 2010)

2.9.5 Ultimate analysis

Elemental analysis for carbon, hydrogen, oxygen, nitrogen and sulphur (CHONS) is performed especially where empirical models are to be employed in estimations of the energy content of the MSW as a fuel particularly for thermal based WtE methods. Laboratory methods usually involving the CHONS analyser and atomic absorption spectrometry are normally employed for these tests. In some case, MSW samples are pulverised and analysed for heavy metals in order to determine presents of contaminants. Tests for chlorine are also performed especially where there is need to determine the corrosive properties of the MSW stream on the boiler equipment surfaces. Elemental analysis also assists in predicting the composition of flue gases and in designing appropriate flue gas clean-up systems (Panepinto & Zanetti, 2018).

2.9.6 Calorimetry

Calorimetry in determining energy content is usually desired where precision and accuracy is at stack (Basu, 2010). The limitation is that it is more ideal for fuels with a high level of homogeneity and therefore less desirable for unprocessed MSW because the high variability of MSW makes it difficult for a representative sample to be collected for laboratory analysis (Di Maria & Lasagni, 2017). The representability of a 5 gram sample to million tonnes of heterogeneous material remains questionable to date. Nevertheless, calorimetry is important in determining the energy content of MSW as a solid fuel. Normally, higher heating values (HHV) are obtained from calorimetric tests on the fuel sample and lower heating values (LHV) are subsequently calculated. The heating value represents the amount of heat released during the combustion of a specific amount of fuel when compared to a unit of weight or volume of the fuel (Basu, 2010). LHV is therefore more important because HHV is inflated due to inclusion of the latent heat of vaporization due secondary products formed during the thermal conversion process.

2.10 Selecting the ideal waste-to-energy technology

The choice of WtE technology is a critical step in solving waste management problems. If this step is not performed well, the result may be mere substituting one environmental problem with another. For instance, technologies which present problems to the nearby community in terms of pollution will quickly stir public skepticism and attract opposition (Bag et al., 2016). While choice of technology must be guided by the primary objectives of the WtE program, due consideration must be given to the three facets of sustainability: environmental, techno-economic and social. The interlocking 3 circles of sustainability shows the that the sustainability metrics are those that fully and simultaneously address the economic, environmental and social aspects (Fig. 2.8)

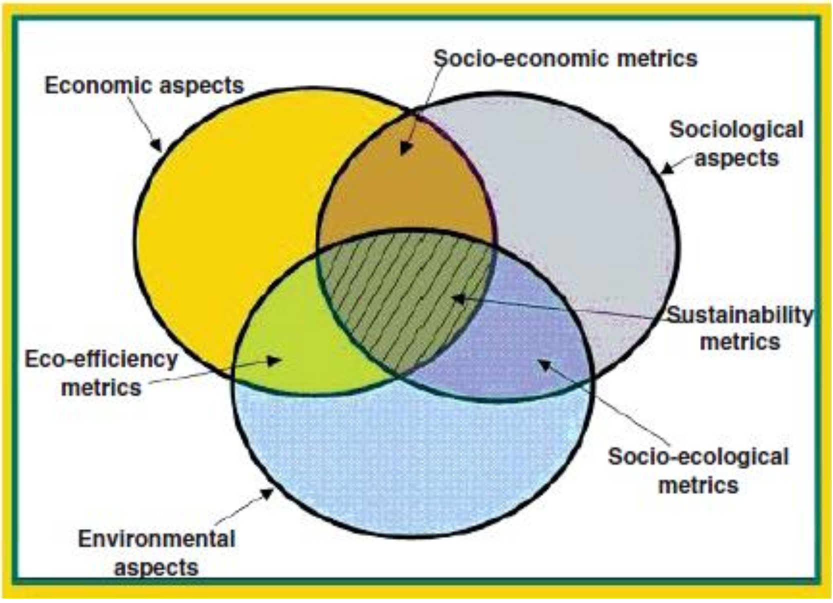

Fig. 2.8 Economic, environmental and social aspects of sustainability metrics

Source: Millward-Hopkins et al., (2018)

Each of the three dimensions of sustainability is important in guiding choice of WtE.

2.10.1 Importance of techno-economic aspect of WtE project sustainability

The techno-economic feasibility of WtE projects is the primary consideration that must be made. Before environmental and social sustainability assessments are made, it must be demonstrated that technically the technology is applicable in the context of the specific study area, and that its commercialization is also technically feasible. There are quantity and quality limits associated with each technology. For example, the World Bank (1999) recommends that for MSWI to be technically feasible, the total combustible fraction of the MSW must be at least 50 000 MT/yr., and its energy content must be a minimum of 7.0MJ/kg. Never at any time throughout the year must the energy content of the MSW be less than 6.0 MJ/kg.

Additionally, most WtE projects in developing countries are operated as Public Private Partnerships (PPPs) due to their capital intensive nature. As such, they should attain reasonable economic viability otherwise once started they will quickly grind to a halt due to poor financial performance. Regular income sources include tipping fees, sale of heat and electricity as well as sale of recycled and recovered materials including ferrous and non-ferrous metals. Often the government may award short or long term feed-in-tariffs (FITs) as an incentive to promote such green projects. With or without such FITs, the projects must be operated with economic viability.

2.10.2 Importance of environmental aspect of WtE project sustainability

The environmental aspect is equally critical. WtE primary objective is to solve an environmental problem i.e. poor waste management. It is therefore critical that devised solutions are not a replacement of one environmental problem with another. WtE thermal power plants may generate toxic waste. Air emissions may be sources of dioxins, PCBs, PAH etc. if combustion processes lack effective flue gas cleaning mechanisms. CO_2, CH_4, NOx, SOx are present in emissions from WtE systems and an evaluation of these is important in understanding the impact of WtE systems to the environment. Often, excessive pollution by WtE thermal plants is a reason for their closure by regulatory authorities (Bag et al., 2016). On the other hand successful WtE contributes to GHG mitigation by producing energy which could have otherwise been generated through fossil fuel combustion (C.-C. Chen & Chen, 2013). It also leads to a reduction in landfill space depletion by reducing volume of waste through biochemical or thermochemical treatment. In addition, WtE reduces pollution of land, surface and groundwater that could otherwise occur if the waste was to be dumped in the environment without prior treatment. For sustainable operation, there is need to minimize negative environmental impacts while optimizing benefits.

2.10.3 Importance of social aspects to WtE project sustainability

Sustainability without addressing the need for socially acceptable projects is half-backed. The public will accept projects that add some social value to them. In modelling barriers to solid waste energy practices Bag et al., (2015) noted that, ‘limited community participation arising from low public involvement intensifies public scepticism and attracts public opposition. The US National Oceanic and Atmospheric Administration (NOAA) technical memorandum defines the term ‘social impact’ as “the consequences to human population of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs and generally cope as members of society" (NOAA (US), 2013).While WtE projects may benefit the overall energy system of a country, often the local community bears the direct burden of WtE in the form of pollution, health effects and noise from refuse trucks and plant operations. This local community is the one that will easily participate in public protests that may force projects to close down. A sound Public Participation and Corporate Social Responsibility (CSR) is therefore critical to ensure social sustainability of WtE projects.

2.11 Material flow analysis in waste-to-energy management

By definition, material flow analysis (MFA) is a systematic assessment of the flows and stocks within a system in space and time (Brunner & Rechberger, 2004). The approach is based on the first law of thermodynamics which entails conservation of matter. MFA can be used as a tool to examine the pathways taken by the MSW stream from a given area in order to guide management decisions. Most importantly, MFA can be used to evaluate the effectiveness of a waste management system in order to develop and implement corrective action (Allesch & Brunner, 2017). Results of MFA are presented in an easy-to-understand way that clearly shows the pathways taken by the various MSW streams (Fig. 2.9) which simplifies decision making.

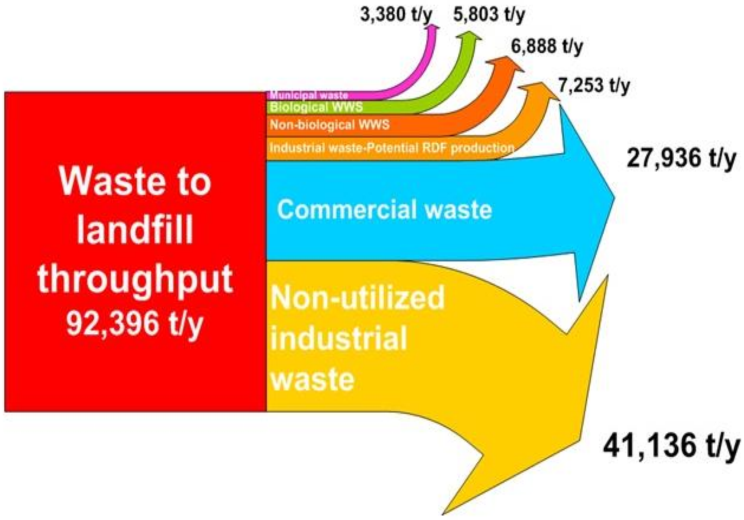

Fig. 2.9 Typical MFA presentation related to MSW

Source: EGC, (2017)

In evaluating the effectiveness of a waste management system, important indicators include the following:

(i) Per capita MSW generation

Waste generation is closely tied to the population and the volume of waste produced inevitably grows with the population (Amit Kumar, Holuszko, Espinosa, & Crocce, 2017; United Nations, 2015). The per capita MSW generation is an extremely important indicator for environmental pressure especially where comparisons with other cities and countries are necessary (World Bank, 2012). The unit of per capita MSW generation is normally kg/capita/day.

The effective MSW recycling rate

Generally, the MSW recycling rate represents the quantities of waste recycled expressed as a fraction of the primary waste generation (World Bank, 1999). Waste prevention, reduction and recycling are the first in preference in terms of the waste management hierarchy. Hence the level of waste recycling shows how sound the waste management is. Most countries set recycling targets and the waste management system must be evaluated in order to know if these targets are being met.

(ii) The MSW collection efficiency

Waste collection efficiency is an important indicator for the effectiveness of a WMS. Many industrialized countries have attained near 100% waste collection efficiency while the average for African countries is 46% (World Bank, 2012). Improving the waste management system must be tied with an increase in waste collection efficiency. When a materials flow approach is adopted, waste collection efficiency below 100% means there is an accumulation of materials somewhere in the system and in most cases, this represents waste buried at source or dumped indiscriminately in the environment.

(iii) The MSW collection burden

This indicator is closely related to the MSW collection efficiency and it represents the relationship between the quantity of waste generated and that which the managing authority must collect. Interventions involving waste reuse at source reduce the overall waste collection burden on the municipality. Additionally, where recycling companies collect source-separated recyclables, the overall burden on local authorities is also reduced. This is particularly important because the cost of waste collection is directly correlated to the quantity of MSW that must be collected (Fernández-Aracil, Ortuño-Padilla, & Melgarejo-Moreno, 2018). A lower waste collection burden represents a healthier waste management system because fewer resources have to be expended in collecting residual waste and transporting it to the landfill (Aleluia & Ferrão, 2017).

(iv) Landfill lifespan

Effective waste management systems must demonstrate an ability to divert as much waste from landfills as possible in order to prolong its lifespan. This is particularly so because modern goals of waste management must include conservation of materials and space (Malinauskaite et al.,2017). Minimising residual waste by increased recycling and diversion for waste treatment is key to extending landfill lifespan.

(v) Landfill gas (LFG) emissions

When the organic fraction of MSW (OFMSW) decomposes in landfills, LFG is produced and may contain methane (CH_4), carbon dioxide (CO_2) and other non-methane organic compounds (NMOC) in various proportions depending on the composition of the waste and the prevailing climatic conditions (Cucchiella, D’Adamo, & Gastaldi, 2017). Sanitary landfills are normally designed with mechanisms for releasing LFG for safety and environmental reasons in which case the LFG can simply be recovered and flared (Guyer, 2009). Landfill gas to electricity installations take advantage of this feature in order to use the LFG for electricity generation as has been described in previous sections.

2.12 Scenario analysis

Modelling in waste management is not a new practice. It serves as an important tool for making a holistic rather than isolative approach to analysing systems with complex interactions. Often, wrong management decisions are made where important system interactions were either underestimated or completely ignored. Pei Qin Ng, Loong Lam, Varbanov, & Klemes, (2014) demonstrated the applicability of modelling in optimizing economic performance of a WtE network by using criteria that sought to minimise cost and maximise returns in the form of electricity generated and landfill space saving. Fruergaard & Astrup, (2011) applied life cycle assessment (LCA) to prove that waste incineration with efficient energy recovery was the most competitive solution (in comparison with co-digestion of coal and solid recovered fuel) in Denmark.

Scenario analysis is defined as a process of analysing possible future events by considering alternative possible outcomes. It centres on making reasonable predictions on the possible future, the probable future and the plausible future (Duinker & Greig, 2007) which represent what may happen, what is most likely to happen and what we would prefer to happen.

Methods of scenario analysis can be divided into two types: one that projects forward with a set of fixed scenarios and alternative futures to be considered and another that projects backwards with fixed futures and various alternative routes for attaining to the selected fixed futures (Complexia, 1998) (Fig. 2.10).

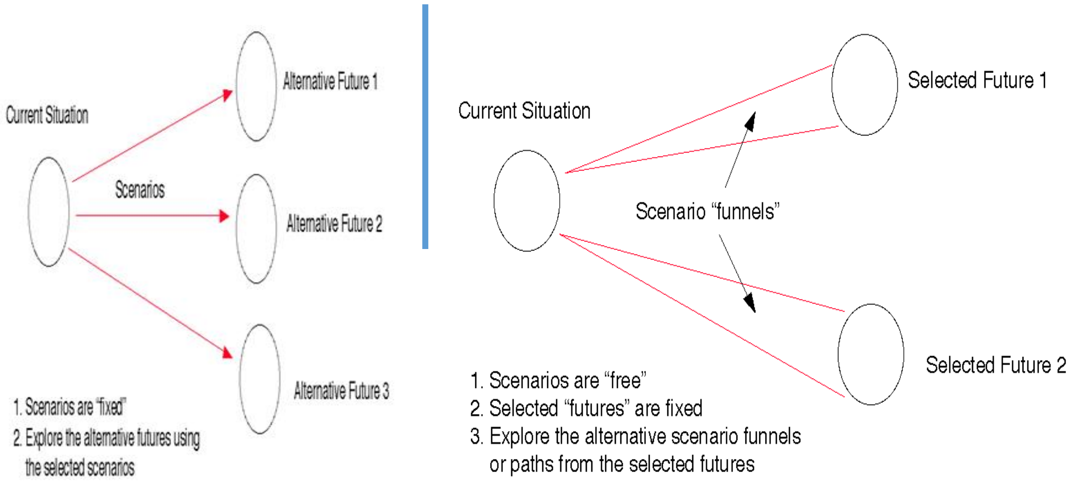

Fig. 2.10 Scenario analysis methods

Source: Complexia, (1998)

The procedure for scenario analysis begins by defining the purpose and spatial and temporal scope of the analysis. Each scenario is then described in a story line where underlying assumptions are stated. For fair comparisons, it is best to assume common assumptions wherever possible so that the outcomes are in as much as is possible, determined only by the unique aspects of each scenario. Each scenario is then evaluated in terms of the selected outcome variables. Finally a sensitivity analysis is performed to evaluate how the outcomes would change with some changes in the scenario assumptions. This is illustrated in Fig. 2.11 and Fig. 2.12

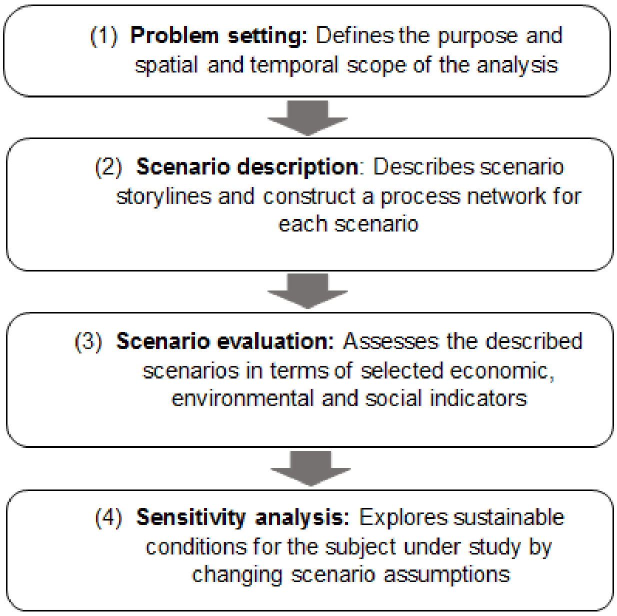

Fig. 2.11 Procedure of Scenario analysis method

Source: Adapted from Kishita, et al., (2017)

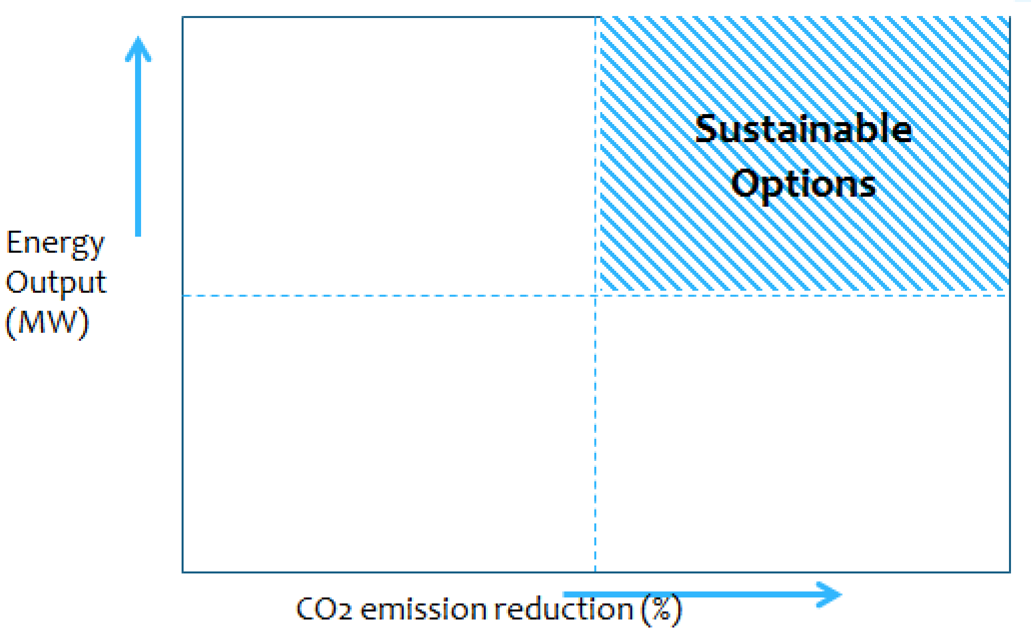

Fig. 2.12 Scenario evaluation on the basis of energy output and CO_2 emission reduction

Source: Kishita et al., (2017)

2.13 Multi-criteria decision analysis (MCDA)

The scenario setting reviewed above usually leads to a complex decision problem involving numerous and often conflicting evaluation criteria. In solving such problems, specialized tools are used which assist in evaluating the real welfare changes arising from each option. Among these tools are monetary based techniques such as cost benefit analysis (CBA), cost effectiveness analysis (CEA), financial analysis (FA), and non-monetary techniques such as multi-criteria analysis (MCA), life cycle assessment (LCA) or exergy analysis (Abhishek Kumar et al., 2017). The development of a waste management policy, programme or project goes through identifying objectives, identifying options for achieving the objectives, selecting criteria for use in comparing the options, analysing options and making the choices. This is the decision making process. MCA is a decision making tool for establishing preference between options by reference to an explicit set of objectives that the decision making body has identified and for which it has established measurable criteria to assess the extent to which the objectives can be achieved (DET, London, 2009). Multi-criteria decision analysis (MDCA) is one the most widely used forms of MCA globally (Abhishek Kumar et al., 2017).

The advantages of MCDA over many monetary based assessments include the following, adapted from DET, London, (2009), Abhishek Kumar et al., (2017), and 1000minds, (2018):

- MCDA simplifies decision making by avoiding the need to convert every benefit, cost, risk, opportunity into monetary values (as is the case with CBA, CEA, and FA).
- MCDA allows both quantitative and qualitative tools to be used in a single decision framework;
- When compared to such tools as life cycle assessment (LCA), or exergy analysis, MCDA proves superior in removing the idea of using one criterion (e.g. CO_2 emissions) as the means of evaluating options. For sustainability assessment all

necessary economic, environmental and social sustainability metrics must be explicitly applied;

- MCDA is a transparent and repeatable process and software has been developed to aid in synthesising complex data sets;
- The choice of objectives and criteria is open to analysis and modification if they are deemed inappropriate which provides room for new options to be identified during the decision making process.
- It allows subcontracting performance measurement to experts other than the decision makers themselves, which removes the burden from analysts or decision makers;
- MCDA provides a means of communication between decision makers and the wider community which improves public ownership of waste management programmes, policies, and projects.
- The use of weights established according to proven techniques leaves a good audit trail which is important for review and continuous improvement.

Software exists for MCDA including MACBETH, decision table, diviz, 1000minds and Visual PROMETHEE. The choice is informed by the nature and objectives of the analysis to be made or simply by accessibility to the software (DET, London, 2009).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction and research framework

The current study began by reviewing secondary data pertaining to the waste problem in Harare metropolitan province as well as demographic data pertaining to Zimbabwe as a whole. Indications that the country's waste management system (WMS) was ineffective were apparent as has been discussed in Chapter 1 and 2. Despite the government having announced a new integrated solid waste management plan (ISWMP) in 2014, there was little evidence regarding progress in terms of achieving the goals and objectives of the plan. Therefore, there was need to understand the problem in greater detail in order to allow for the design of appropriate corrective actions in line with the ISWMP. First, in order to illustrate the magnitude of the problem more quantitatively, material flow analysis (MFA) had to be performed. Secondly the waste had to be examined further in order to appreciate its value as a possible feedstock for energy recovery. Finally possible solutions had to be proposed and through scenario analysis, evaluated by using appropriate tools capable of handling complex problems involving multiple criteria. Finally, one technology had to be selected with consideration of techno-economic, environmental and social sustainability criteria. This chapter provides a detailed explanation of the various methodologies and techniques applied in carrying out these assessments. Fig. 3.1 illustrates the research framework.

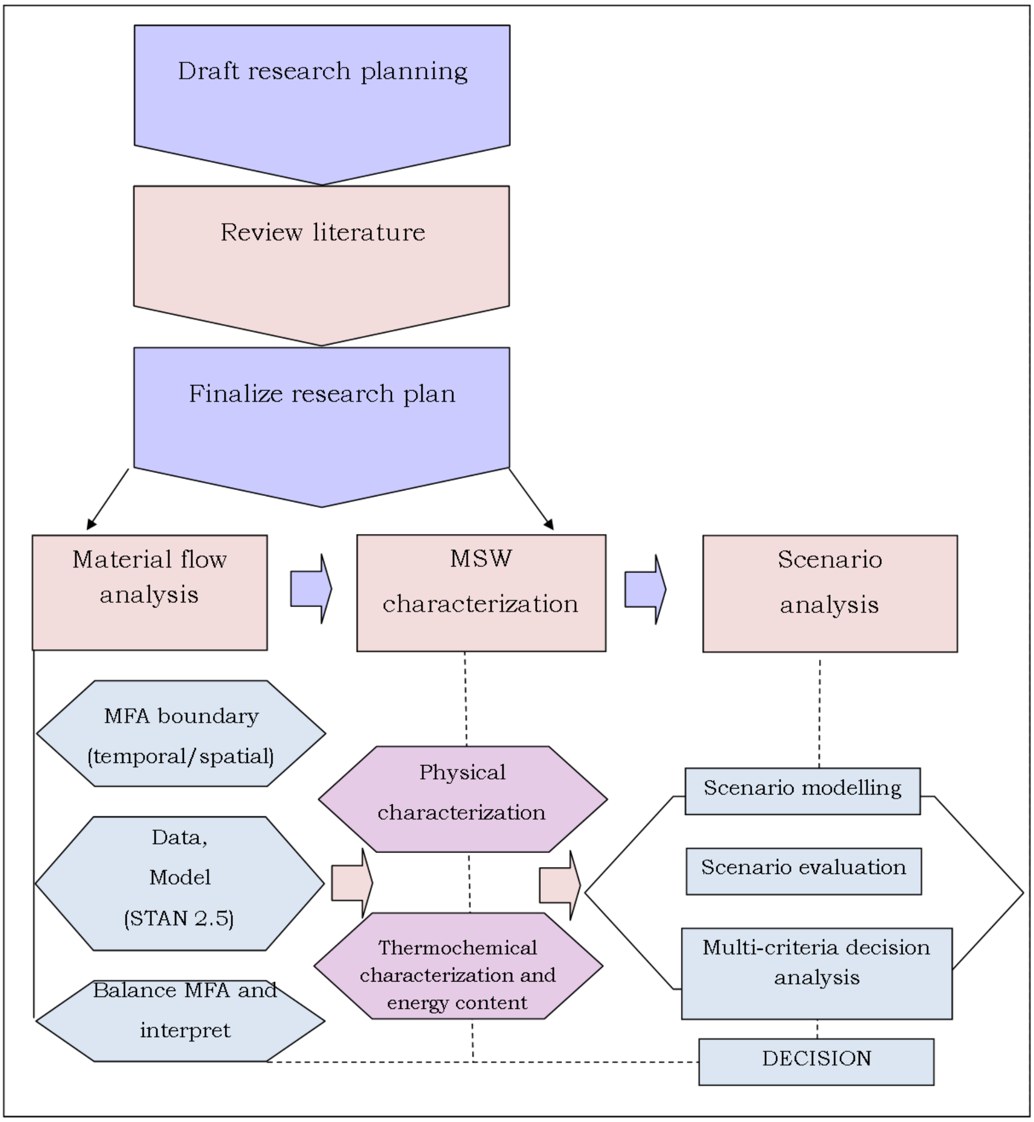

Fig. 3.1 The conceptual framework for the present study

3.2 Study area

3.2.1 Physical location and background information

Harare metropolitan province is one of the ten provinces in Zimbabwe. Its administrative capital is Harare which is also the capital city of Zimbabwe. The province includes Harare, Chitungwiza and Epworth and is home to about 2,098,199 people (ZNSA, 2015). The three areas are managed by three local authorities namely Harare City Council, Chitungwiza City Council and Epworth Local Board respectively. The province is approximately 960.6 km^2 in size (Fig. 3.2). While Harare is the hub of industrial and economic activity, the latter two are predominantly residential towns with very little industrial activity. The province is located north-east of Zimbabwe in Region

IIA in terms of the ecological classification system of Zimbabwe (OCHA, 2016). Harare is itself a plateau situated at an elevation of 1,483 metres and its climate falls into the subtropical highland category. It is the leading financial, commercial and communications centre for Zimbabwe. The industrial hub of Harare produces goods like steel, chemicals, and textiles, processed food products including beef, poultry, vegetables and cereals. It is also the hub of Zimbabwe's service industry with both public and private sector industries dominating the Central Business District (CBD). By reason of the high population density, the province generates the largest volume of MSW in comparison with other provinces in the country. The Harare City council manages MSW generated in areas which make up Harare such as Mbare, Mt. Pleasant, Glenview, Dzivarasekwa and Highlands. Chitungwiza Municipality manages MSW generated in areas that make up Chitungwiza including St Mary's, Makoni and Zengeza. MSW generated in Epworth is under the care of Epworth Local Board. Harare metropolitan province was selected for the purpose of this study for the following reasons:

- It houses 49.5% of Zimbabwe's urban population making it the largest contributor to the MSW share. Not surprisingly, the province is the worst affected in terms of waste management challenges.
- It represents the hub of economic activity of the northern part of Zimbabwe, Chitungwiza being the major residential town for most people working in the city of Harare;

3.2.2 Climate and related information

Zimbabwe's climate is predominantly tropical though moderated as a result of the country's higher altitude in comparison to its neighbours. It has four distinct seasons: hot and wet summer, cooler but drier autumn, cold and dry winter, and hot and dry spring. The climate is heavily influenced by the Inter-Tropical Convergence Zone (ITCZ) and partly by altitude and relief. Rainfall ranges from 450mm in the Limpopo and Zambezi Lowveld to 1,050 mm in the Eastern highlands. Harare receives an average of 810 mm per annum. In the Highveld, temperatures range from an average of 12.5^{o}C in winter to 24^{o}C in summer while in the Lowveld average temperatures range from 32^{o}C to 38^{o}C (OCHA, 2016). In comparison to the rest of Zimbabwe, Harare is located on a plateau at 1,483m and temperatures range from 6.3^{o}C to 22.2^{o}C with an average of 18.4^{o}C. The summers are humid subtropical while the winters are drier. With these conditions in mind, moisture content of discarded MSW is generally expected to be highest during the rainy summer period and lowest during the drier and cooler winters.

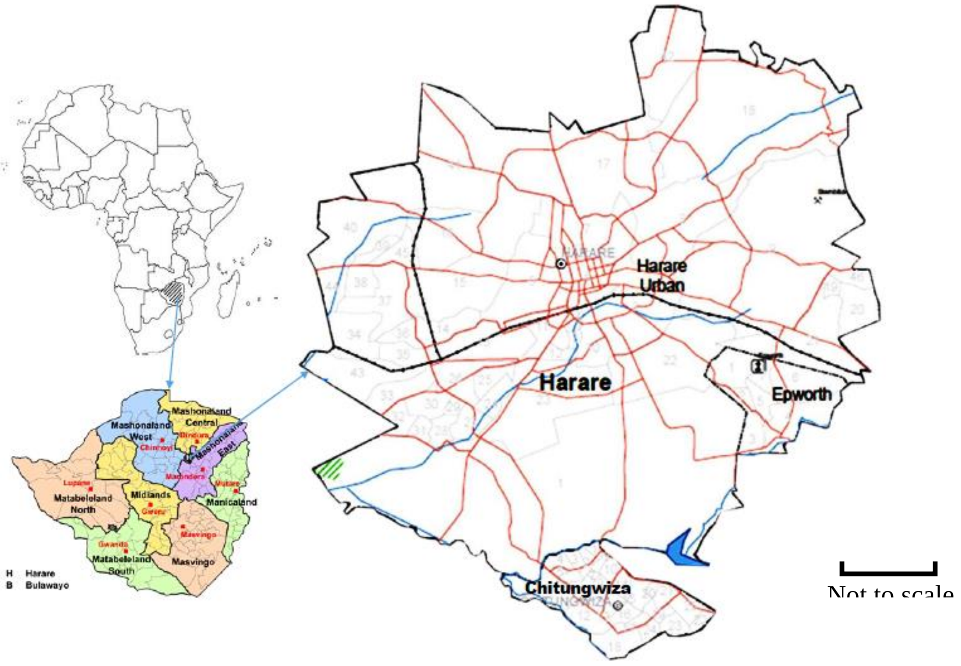

Fig. 3.2 Harare metropolitan province map

Source: OCHA, (2016)

3.3 Methodology for Material flow analysis

3.3.1 MFA scope and boundary

The objective of the MFA was first to provide a quantitative analysis of the waste problem in Harare Province (spatial boundary) by visualizing flows, stocks and sinks of MSW (representing goods) for the year 2017 (temporal boundary) and subsequently to evaluate opportunities for waste prevention, reuse, recycling and energy recovery. The political boundaries of the province as shown in Fig 3.2 defined the spatial scale according to the MFA concepts in (Brunner & Rechberger, 2004)

3.3.2 MFA Data sources

The current study adopted the mass balance technique as the main methodology in visualizing flows, stocks and subsequent sinks for MSW in the study area for the year 2017. The following data sources were used:-

- The year 2011 was set as the base year because of the comprehensive data gathered during a nationwide survey by the Institute of Environmental Studies (IES).
- A survey was repeated by the Environmental Management Agency (EMA) in 2016 and the data still remains as an unpublished report (EMA, 2016).
- The MSW characterization data (Section 3.4)
- Local authorities waste disposal and waste recovery records obtained at the waste disposal sites
- Informal waste collectors working at these sites were also interviewed.
- A waste recycling companies' database was accessed from EMA and it provided useful data which was used in contacting and visiting recycling companies in order to quantify waste absorbed by formal and non-formal recycling and waste produced from recycling activities.
- Three separate interviews were held with officials from each local authority. During the interviews, the local authorities' waste management records were also inspected and the data was compared with that obtained at the waste disposal sites.
- The only incineration plant in Harare lacked recent data and a recording template was provided to the operators in order to collect the required data (the data was however not used in the final consolidation as the facility only handles health care wastes)
- The main private waste collectors' record were also inspected;

Data uncertainties in MFA are a critical issue as large data variations can reduce the reliability of the MFA results (Laner, Rechberger, & Astrup, 2014). Hence for estimates, the data variations within 10% of data extrapolated from the last credible records were accepted which is consistent with similar studies (Zaccariello, Cremiato, & Mastellone, 2015). Any larger variations prompted for more data sourcing and validation. Table 3.1 shows the final consolidated data used in the MFA. The MFA software, STAN version 2.5, was uses for performing the mass balances in accordance with the Australian Standard O Norm S 2096 (Material flow analysis- Application in waste management) (Cencic, 2012).

Table 3.1 The consolidated data input for MFA model

Processes and units	Label	Description	Input values (MT/Yr.)	Input transfer coefficients (where applicable)	Data uncertainty (%) for estimates
Primary waste generation (MT/yr.)	PWG	Import flow	421,757.00		n/a
Waste transported from other cities (MT/yr.)	PE	Import flow	240.00		0.08
Waste recovery and recycling (before disposal) (%)	FNFR	Intermediate flow		0.123	n/a
Waste collection by urban local authority (%)	FC(LA)	Intermediate flow		0.441	n/a
Waste collection by urban private companies (%)	FC(P)	Intermediate flow		0.029	n/a
At-source burning/burying (%)	SS	Intermediate flow		0.367	n/a
Open dumping of waste (%)	OD	Intermediate flow		0.040	n/a
Accumulation in landfills (MT/yr.)	n/a	Stock	n/a	n/a	n/a
Accumulation in the illegal dumps (MT/yr.)	n/a	Stock	n/a	n/a	n/a
Accumulation in household pits (MT/yr.)	n/a	Stock	n/a	n/a	n/a
Waste recovery from open dumps (%)	WROD	Intermediate flow		0.60	0.06

Processes and units	Label	Description	Input values (MT/Yr.)	Input transfer coefficients (where applicable)	Data uncertainty (%) for estimates
Waste recovery from open dumps (%)	WROD	Intermediate flow		0.15	0.06
<u>Waste management by private companies</u>					
(i) Waste recovered for recycling (%)	FNFR	Intermediate flow		0.2	0.08
(ii) Waste transferred to landfill/ waste disposal site (%)	FC(P)			0.8	0.08
<u>Waste management at recycling facilities</u>					
Goods produced from recycling (MT/yr.)	GFW	Export flow	45,000.00	0.8-0.9	n/a
(ii) Waste transferred to landfill/ waste disposal site (%)	WRA	Intermediate flow		0.1-0.2	n/a

3.3.3 Evaluation criteria

The criteria used to evaluate the effectiveness of Harare's waste management system are listed as follows

i. The per capita waste generation
ii. The effective recycling rate
iii. The waste collection efficiency
iv. The waste collection burden (on local authorities)
v. Landfill lifespan
vi. Landfill gas emissions from residual waste

The specific details of these criteria have been reviewed in Section 2.11 and the calculations are provided in Appendix B.

3.4 Assessment of MSW composition, physical and thermochemical properties

3.4.1 Sampling-materials and methods

The minimum list of materials used was as defined in ASTM D5231-92(2016) (ASTM, 2016) (Fig. 3.3).

Fig. 3.3 Field survey kit

(Composed of tarp, buckets, cutting instruments, field scale and protective clothing)

Main laboratory instruments included:-

- Sample shredding and preparation kit (shredder, hand tools, pair of scissors and knife, and scalpels).
- Standard electric oven and metal tongs
- Electric furnace
- Metal trays and ceramic crucibles (withstanding +1000^{o}C)
- Laboratory scale or balance (sensitivity/readability 0.01mg)
- Desiccators.
- Calorimeter
- Elemental analyser

3.4.2 Determination of number of samples

Mixed paper and plastics are selected as the governing component in determining the number of samples as provided by the ASTM D5231-92 standard (ASTM, 2016)

3.4.3 Coning and quartering

Thirty eight (38) MSW samples were collected and sorted over a three-week period in July and August 2017. 24 samples were collected and analysed at Pomona, the MSW disposal site for Harare while 14 samples were analysed at Chitungwiza and Epworth. The sampling was varied this way because the largest MSW throughput is in Harare (up to 80%). Each sample was reduced by repeated coning, mixing and quartering until an appropriate sorting sample was attained. Segregated waste components were placed in pre-weighed plastic containers equipped with tight-fitting lids (Fig 3.4). Sorting continued until the residual fines were less than 5mm in diameter which were added to either ‘other fines’ or ‘rubbles’ depending on whatever category they were mostly composed of. The waste discarded at the end of randomly-selected quartering exercises was used for bulk density assessments.

3.4.4 Bulk density assessment

Bulk density assessment was conducted on 22 samples due to the wide variation expected for unprocessed MSW (Stoltz et al., 2010). The mass per unit volume technique was followed which involves filling up a pre-weighed container with waste and dropping it thrice from a point approximately 10cm above ground level thereby allowing the waste to settle before filling up the container and re-weighing (EPA, Ireland, 1996;Huerta-Pujol et al., 2010). For each sample, the bulk density was calculated using eq.3.1

$$\text{Bulk density} = \frac{(w_2 - w_1)}{V_1}\ kg/m^3 \qquad [3.1]$$

Where W_1 is initial weight of the empty container in kg;

W_2 is final weight after executing the procedure in kg and

V_1 is the volume of the container used in m^3

Fig. 3.4 Waste sorting (with assistance from local research students and informal waste collectors) during the field survey

3.4.5 Sample drying and further preparation

Due to the high heterogeneity of MSW, the application of thermogravimetric (TG), ultimate or bomb calorimetric tests demands the preparation of samples to obtain fine mixtures representative of the original MSW stream (Lombardi et al., 2015;Robinson, Bronson, Gogolek, & Mehrani, 2016). Reconstituted[2] samples can be used for TG experiments, ultimate analysis and energy content analysis with high reliability of results (Hla & Roberts, 2015). For each of the three areas, 8-12 samples weighing between 400-500g each and consisting of separated waste components were spread in 4 trays and oven dried at 90±2°C for at least 24 hours in line with the method outlined by the Irish EPA (EPA, Ireland, 1996). Food wastes were spread as thinly as possible to facilitate rapid moisture loss. After drying, the samples were cooled to room temperature and re-weighed. Moisture content as discarded was determined using equation 3.2.

The waste components were further shredded using a laboratory cutting and grinding mill and sieved using an internal 250µm sieve. Thin plastics were first hardened by compression moulding and trimmed into a 1-3mm RDF before milling to the required sizes. Fibrous and high-strength components such as textiles, HDPE and PET were first manually trimmed to less than 3-5mm to ensure they do no wrap around or damage the shredder blades. Sieving of ground materials was repeated using a hand-held 300µm fine mesh sieve to ensure any oversized particles forced into the grinder tray as a result of the high-speed shredding and grinding are eliminated. Samples were kept in sealed polythene packets and stored in a desiccator pending further analysis.

3.4.6 Moisture content analysis

For every waste category, the moisture content was determined after complete oven drying by considering the mass difference. Eq. 3.2 was used to calculate the moisture content. (Presented by EPA, 1996 and also used by Boumanchar et al., 2017)

$$\%H_2O = \left(\frac{W_1 - W_2}{W_1}\right) x100 \qquad [3.2]$$

Where W_1 is initial weight the sample (*g*);

W_2 is final weight after moisture loss (*g*)

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[2] Additional information is provided in Appendix B.

3.4.7 Proximate analysis

Proximate analysis involves laboratory examination of a sample of the MSW for moisture content (MC), volatile matter (VM), fixed carbon (FC) and ash, parameters of which are important in evaluating the combustibility of the waste in the absence of auxiliary fuel. VM and ash content are particularly important measures as they reflect the heating value of MSW as a fuel and what remains on grates as residue after combustion respectively (Robinson et al., 2016). Thermogravimetric (TG) experiments were performed according to standard techniques based on ASTM E872-82(2013), ASTM E987-87(2004), and ASTM E1756-05 (2015) (ASTM, 2015a;ASTM, 2015b;ASTM, 2013a). First, 3-4g of the prepared and reconstituted samples[3] was oven-dried in a fan-assisted oven at 105°C for 1 hour, cooled and re-weighed. Secondly, they were ignited at 750°C for 2 hours in covered crucibles, cooled and re-weighed. Finally, they were ignited at 550°C for 1 hour in open crucibles, cooled and reweighed (Fig 3.5). Proximate values were calculated and normalized.

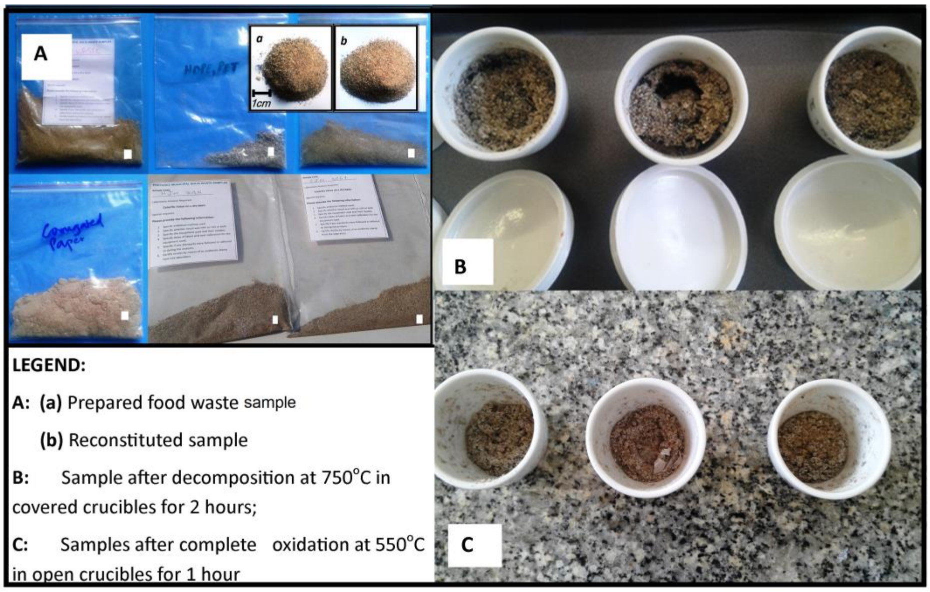

Fig. 3.5 Samples before and after thermal decomposition

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[3] See Appendix B for composition of reconstituted samples and additional notes

3.4.8 Ultimate analysis

Ultimate analysis is the determination of carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O). Carbon and hydrogen represent the oxidative potential of MSW as a fuel while nitrogen and sulphur are quick pointers for the expected quality of the flue gases from thermochemical treatment (Brown, 2011). Nitrogen is also important in determination of the C/N ratio where biochemical treatment of the waste is being considered (Tanimu, Ghazi, Harun, & Idris, 2014).

Ultimate analysis was performed on prepared oven-dried MSW samples weighing between 12.2 mg and 12.7 mg using a CHNS/O elemental analyser (PerkinElmer, 2400 series II) which utilizes a combustion technique to decompose the sample into the various combustion gases- CO_2, H_2O, N_2, SO_2, which were then separated using frontal chromatography before detection in the final thermal conductivity (TC) detection zone.

3.4.9 Energy content of MSW

The heating value represents the amount of heat released during the combustion of a specific amount of fuel when compared to a unit of weight or volume of the fuel (Brown, 2011); (Hosokai, Matsuoka, Kuramoto, & Suzuki, 2016) Literature also commonly refers to HHV as gross calorific value and LHV as net calorific value. The higher heating value can be obtained experimentally by using a Bomb calorimeter (Zhou, Long, Meng, Li, & Zhang, 2015; Hosokai et al., 2016). Additionally, where elemental values of C, H, N, S and O have been obtained, the energy content can be estimated using empirical formulae (Siddiqui, Zaidi, Manuja, Pandey, & Khan, 2017;Thipkhunthod et al., 2005).

For MSW, the lower heating value on a wet basis (LHV_{wb}) is by far the most important measure of its worth as a fuel because thermal-based WtE processes must expend energy in driving out residual moisture in the feedstock before useful heat is recovered from the combustion chamber (Brown, 2011). Hence in order to report the LHV_{wb} the moisture content reported in the current study must be accounted. Eq. 3.3 adapted from Hla and Roberts, 2015 was used.

$$LHV_{wb} = LHV_{db}\,(1 - MC\ x\ 0.01) \qquad [3.3]$$

Where:-

- LHV_{wb} is the lower heating value on a wet basis

-LHV_{db} is the lower heating value on a dry basis

-MC is the measured moisture content obtained in Section 3.4.6.

The higher heating value (HHV) of reconstituted samples was measured directly using an IKA C5000 control bomb calorimeter through a method compliant with ASTM 5468. The lower heating value was also estimated from ultimate analysis data using the modified Dulong equation (eq. 3.4) (Hosokai et al., 2016).

$$LHV_{db}\,[kJ/g] = 38.2m_C + 84.9\,(m_H - m_O/8) - \Delta H_1 \qquad [3.4].$$

Where m_C, m_H *and* m_O *are the contents of carbon, hydrogen, and oxygen obtained from ultimate analysis and* ΔH_1 *is the measure of the latent heat.*

The value for ΔH_1 for solid fuels is 0.62KJ/g. For uniformity, the result is expressed in MJ/kg.

Direct measurement of dried samples on the calorimeter produce the result as higher heating value on a dry basis (HHV_{db}) which must also be converted into LHV_{db} and finally to LHV_{wb}. The HHV is a slightly exaggerated value for the energy content as it includes the latent heat of condensation which is not part of the energy present in the fuel. As has been explained above, the LHV on a wet basis is more important because HHV is inflated due to inclusion of the latent heat of vaporization of water as a result of secondary products formed during the thermal conversion process (Hla & Roberts, 2015;Hosokai et al., 2016). The European Committee for Standardization (CEN) developed eq.3.5 which was used to calculate LHV$_{db}$ from HHV (CEN, 2009;Hla & Roberts, 2015). Eq 3.6 was finally used in calculating LHV$_{wb}$ from LHV$_{db}$.

$$LHV_{db} = HHV_{db} - 0.2122\ x\ H - 0.0008\ x\ (O + N) \text{ MJ/kg} \qquad [3.5]$$

Where H, O and N are the mass composition for hydrogen, oxygen and nitrogen

$$LHV_{wb} = LHV_{db}\ (1 - \%MC\ x\ 0.01) - 2.443\ x\ \%MC\ x\ 0.01 \text{ MJ/kg} \qquad [3.6]$$

Where MC is the measured moisture content for each waste stream and LHV$_{wb}$ is the lower heating value obtained using eq.3.5. The results are presented and discussed in Chapter 4.

3.4.10 Ash and trace elements analysis

Ash and trace metal analysis was performed for 10 trace elements using an X-ray fluorescence (XRF) spectrometer (PW2400, Philips, Netherlands). The procedure adhered to standard in-house methods WI-RES-XRF-001 and WI-RES-XRF-002 developed after ASTM E1621-13, Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry (ASTM, 2013b). The method involved combustion of prepared samples in excess air and calculating the concentration of trace elements from the various metallic oxides. Of greater relevance to the scope of the current paper are results for chlorine because it is the most important indicator for the formations of dioxins, furans and related polychlorinated organic pollutants formed during thermal treatment of MSW (Chen et al., 2017;Edo et al., 2017).

3.5 Methodology for Scenario analysis

3.5.1 Overview

The purpose of this aspect of research has been reviewed in Section 2.12. The next sections will describe the setting for scenario analysis and evaluation. The method followed was adapted from Kishita et al, 2017 and modified to suit the current study as in Fig 3.6

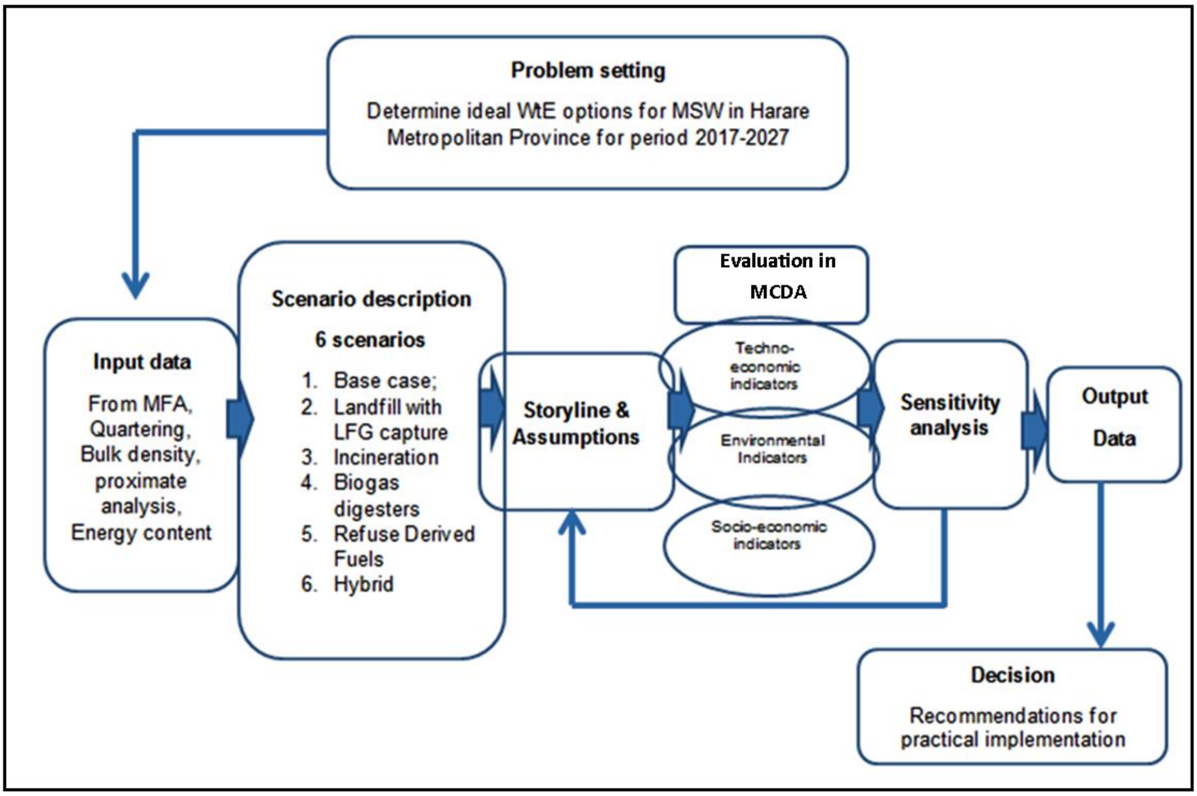


Fig. 3.6 The scenario analysis framework as adapted to fit the current study

3.5.1.1 Input data

Data from all previous analyses including MFA, physical composition, bulk density, thermochemical properties and energy content are used in shaping scenarios

3.5.1.2 Scenario overview description

6 Scenarios are presented and these are based on technologies whose description has been presented in Table 2.6. Each scenario is assumed to be prevailing over a period of 10 years with the year 2017 being the base year.

1) Base case (also called the business as usual –BAU scenario
2) LFG to electricity
3) AD with biogas and digestate utilisation
4) MSWI (Incineration with energy recovery)
5) RDF for electricity co-generation with coal
6) Hybrid plant (AD and MSWI)

3.5.1.3 The decision context

The aim was to select among the 6 scenarios (including the BAU scenario) the most cost-effective option that offers optimal improvement to Harare Province’s waste management system and guarantees optimal energy recovery with the least impacts to the environment and society.

- Cost-effectiveness: satisfies the economic aspect of sustainability;
- Optimal improvement to the waste management system and optimal energy recovery address the technical feasibility of the options;
- Least impacts to environment addresses environmental sustainability;
- Least impacts to society addresses social sustainability

The guiding principle is that WtE is primarily aimed at waste treatment (volume reduction and inertization), while recovered energy and materials are secondary benefits.

3.5.1.4 Evaluation criteria

The evaluation criteria was listed as follows in line with the sustainability metrics reviewed in Section 2.10

Techno-economic criteria

The total residual waste is one of the most important indicator where WtE treatment is being considered as it reflects the level of waste diversion from landfills (Malinauskaite et al., 2017). Globally, waste diversion rates are highest in EU countries, more so due to scarcity of land for constructing new landfills (World Bank, 2012). Good practice in waste management should therefore be aimed at relieving pressure on landfills by ensuring optimum waste diversion rates.

Capital expenditure refers to the estimated investment costs associated with each option. These are related to treatment capacity and therefore typical values presented in reviewed literature (Beyene et al., 2018; Aleluia & Ferrão, 2017) were used as the primary references.

Operational expenditure refers to the estimated operational costs associated with each alternative. Due to lack of local data to support appropriate modelling of this criterion 3 levels have been identified as low, high, and very high and (Beyene et al., 2018; Aleluia & Ferrão, 2017) were used as the primary references.

The total energy yield associated with each scenario depends on the technology applied and the annual treatment capacity and other factors including fuel to power efficiencies. The energy yield for each option was calculated using input data mentioned in section 3.5.1.1. Details of calculations are presented in Appendix B.

Environmental sustainability criteria

Avoided CO_2 equivalent emissions are calculated for each option assuming the energy produced could have been produced through fossil fuels (coal) combustion. The avoided emissions are therefore a benefit attached to each option depending on the energy yield

Other toxic emissions (NO_2, SO_2, and NMOC) associated with each option are also evaluated. Due to lack of local data to support appropriate modelling, 4 levels are identified as very low, low, high, and very high

CH_4 and other LFG emissions associated with residual waste are evaluated. In this case a % value reflecting the proportion of OFMSW in residual waste is used since it is from this fraction that LFG from landfilled residual waste is generated. The performance of the various options in this regard was evaluated by comparing them against a common value (refer to Appendix B).

Social sustainability criteria

The social sustainability score is the final score obtained from expert judgement against each scenario. Further details on social sustainability are provided in Appendix C.

Other benefits are also reflected by a binary scale for Yes/No indicating whether the option yields additional benefits apart from energy. Digestate and compost were the specified additional benefits.

3.5.2 Scenario storylines, assumptions and modelling techniques

The storyline for each scenario against each criterion, underlying assumptions and the subsequent scenario modelling techniques applied are described in the following subsections. The order in which criteria were presented above is not necessarily followed. Specific calculations are presented in Appendix B.

3.5.2.1 Energy recovery

For each scenario, the energy recovery potential was modelled by making reasonable assumptions and maintaining as much as possible conditions applicable to the study area.

(i) *Base Case*

Since no energy recovery is applicable for the bases case or business as usual (BAU) scenario, the electrical energy output from this option is zero (0) hence the option score on the MCA performance matrix is also 0.

(ii) *LFG to electricity*

In order to estimate the electricity yield from LFG to electricity, a suitable model for estimating methane (and CO_2) from the theoretical landfill was applied. As has been stated briefly above, several models exist and they have been extensively used in many studies including the First Order model (TNO), Multi-phase model (Afvalzorg), LandGEM (USE-EPA), EPER (Germany- UmweltBundesamt) (Das, et al., 2016). LandGem Version 3.02 was selected because of simplicity in terms of input data requirements. It is a Microsoft Excel-based software application that uses a first-order decay rate equation (eq. 3.7) to calculate estimates for methane and LFG generation. LandGEM is the most widely used LFG model and in the US, it is the standard model for industry and regulatory requirements (Das et al., 2016).

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, Lo \left({}^{M_i}\!/_{10} \right) (e^{-kt} ij)$$

[3.7]

Where:

Q_{CH4} = estimated methane generation flow rate (in m^3 per year)

i = 1-year time increment

n = (year of the calculation) – (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (1/year)

L_o = potential methane generation capacity (m^3 per Mg)

M_i = mass of solid waste disposed in the i^{th} tear (Mg or MT)

t_{ij} = age of the j^{th} section of waste mass disposed in the i^{th} year (decimal years)

Further, a LFG collection efficiency of 70% was assumed which is within the range for conventional landfills (ATSDR, 2017)

Due to lack of historical data specific to the study area, conventional input values for *k* from the model were accepted while the input value for *Lo* was adjusted to match typical data drawn from a study by (Biglari et al., 2017). The rationale behind the adjustment is that the *Lo* value depends primarily on the waste composition of waste discarded in landfills, hence an adjustment to match a typical developing country was considered reasonable for the purpose of the estimation.

(iii) *AD with biogas and digestate utilization*

The alternative to LFG to electricity where biochemical WtE options are concerned, AD is designed to optimize biogas recovery. The digestate is also useful as a soil conditioner. In order to operate with economic viability, AD must handle source separated OFMSW or leachate from mechanical processing of mixed MSW (Li et al., 2011)

A theoretical continuous anaerobic digester (CAD) dry system operating on mesophilic conditions at 35^{o}C (hence requiring no additional heating considering Zimbabwe's climatic conditions) was assumed. A total volatile solids (VS) content of 0.258-0.435 kg VS/kg OFMSW is assumed in line with Refs Beyene et al., (2018), and WEC, 2017. Assuming that a Dranco dry digester system with capacity 100 000 MT/yr. has been installed, 4 digester units can be built to treat the OFMSW each with a capacity of approximately 25 000 MT/yr. The hydraulic retention time (HRT) ranges between 15-25 days with specific biogas yield 0.1-0.2m^{3}/kg VS. In order to avoid over-estimation of the biogas output, the lower value of biogas yield per kg wet weight of the feedstock was assumed. The theoretical methane yield was estimated to be 2.22E-07m^{3}. The methane is used in a gas engine system with fuel to power conversion efficiency of 40% (see Appendix B for calculations).

(iv) *MSWI with energy recovery*

A modern MSW incinerator is expected to operate for an average of 8,000 hours per year, allowing time for planned maintenance (Chang et al., 1998). The electrical energy output is a function of the plant's capacity, the lower heating value (LHV) of the MSW and total operating hours. For the current scenario, the following assumptions were made:

- MSWI capacity- 100,000 MT/yr.
- LHV of the MSW- 10.1 MJ/kg (from current study)
- Annual operating hours- 8,000 (default value)
- Power plant fuel to electricity [thermal] conversion efficiency-20%, electricity only configuration (Beyene et al., 2018)

$$Wte\ power\ plant\ capacit = MSWI\ capacity\ x\ LHV x\ thermodynamic\ efficiency$$

$$= \left(\frac{MT}{Yr}\right) x \left(\frac{MJ}{MT}\right) x\ E \quad \text{(MW)} \qquad [3.8]$$

MSWI using moving grates normally handle unprocessed waste and the process begins by mechanical separation of incombustible, bulky and hazardous components which are referred to materials recovery facilities (MRFs). The bulk of the mass is directed to the boiler and air pollution control systems where the energy is utilized in a Rankine system to produce heat and power (Brown, 2011).

(v) *RDF for electricity co-generation*

The following assumptions were made for RDF generation for electricity co-generation with coal.

- The plant capacity for this option is 100,000MT/yr. like other options.
- The energy content of RDF is 16.4MJ/kg, moisture content 7.52% moisture content according to data from current study
- MSW to RDF efficiency- 17% (It varies between 17%-50% according to experience in EU countries, hence the lower limit was considered in order to avoid over-estimations) (Panepinto, Blengini, & Genon, 2015);
- Co-incineration rate- 10% (In EU it varies between 10-30%)
- Assuming thermal efficiency of 20% (Beyene et al, 2015)

(vi) *Hybrid system (AD with biogas utilization and MSWI with energy recovery)*

For this system the assumptions made for the individual technologies (AD and MSWI) were maintained. The only variation is the total treatment capacity which becomes twice as much as the rest of the WtE options. The rationale behind this variation was that the major drawback for a hybrid system is related to the initial investment and operational cost hence the need for trade off in benefits by increased treatment capacity (Chang et al., 1998). The initial investment and successive operational costs are high and halving the capacity for the AD and MSWI plants (so that the total will be 100,000MT) does not lessen the investment and operating cost by significant margins (Aleluia & Ferrão, 2017). Therefore, the idea was to bargain a trade-off between the cost and treatment capacity so that the obvious lower score against cost during scenario evaluation can be compensated by benefits arising from the doubled overall capacity.

3.5.2.2 *Total residual waste*

The total residual waste is that fraction of waste requiring landfilling after any recycling or waste recovery activities have been taken into account (Panepinto et al., 2015). Numerically, the total residual waste [$Q_{(w—res)}$] is therefore the sum of the residual waste from primary waste collection activities [$Q_{(col\text{-}res)}$] and residual waste after the application of each management option [$Q(_{wte\text{-}res})$] as shown in eq. 8

$$Q_{(w-res)} = Q_{(col-res)} + Q_{(wte-res)} \qquad [3.9]$$

The plant capacities as assumed in sub-section 3.5.2.1 above were maintained. Detailed calculations are presented in Appendix B and the evaluation results are discussed in Chapter 4.

3.5.2.3 CH_4 and other LFG emissions from the landfill

Standard models for estimating methane emissions from landfills exist including LandGEM, GasSim and the IPCC 2006 model (Emkes, Coulon, & Wagland, 2015). In the current study, the six options were rated on the basis of how much CH_4 will be generated from the waste decomposing in landfill and that discarded in undesignated areas. For that reason, the primary determining factor is the size of the OFMSW present in the residual waste following the application of each management option since it is from this fraction where unrecovered LFG emissions are released into the atmosphere. Therefore, at this stage, the actual quantities of LFG emissions were not of immediate concern.

As a guiding principle, the results of the 2017 characterisation study were used as reference point in determining the OFMSW (47.7%) and CH_4 recovery efficiency for LFG to electricity and AD with biogas utilization were also taken into consideration. In evaluating the various alternatives, their performances were compared against a common value. Detailed calculations are presented in Appendix B.

3.5.2.4 Avoided CO_2 emissions

For all WtE options where electricity is produced and channelled to the national grid, CO_2 emission offsets are achieved by replacement (CO_2 equivalents that could have been emitted if coal was used as the primary fuel for the electricity generation).The US EPA estimate for life cycle CO_2 emissions for coal is 1,012g/KWh (US EPA, 2015). In this study, a more recent estimate by SIPA, (2017) is applied which is 1,086g/KWh. Calculations are provided in Appendix B.

3.5.2.5 Other toxic emissions

Thermal WtE options emit flue gases containing many toxic pollutants including NO_2, SO_2, HCl, dioxins, particulate matter as has been explained in Chapter 2. For scenario evaluation, a qualitative scale was applied with 3 levels: low, high and very high and these were used as they can be easily applied to each WtE technology option. Judgements were inferred from literature (Brown, 2011; Edo et al., 2017).

3.5.2.6 CAPEX and OPEX

Due to unavailability of local or regional data to support an appropriate modelling tool for capital and operational expenditure, the CAPEX values were estimated on a per tonne of capacity basis based on values presented by (Aleluia & Ferrão, 2017). Operational expenditure is site specific hence literature-derived OPEX values could not be used to represent OPEX values for Harare province. For this reason, a qualitative scale was applied with three levels: low, high, and very high OPEX. Results are presented and discussed in Chapter 4.

3.5.2.7 Social sustainability of WtE options

An expert judgement process involving 10 experts was conducted in line with a procedure presented by Mach, Mastrandrea, Freeman, & Field, (2017). The experts drawn from various fields of professions were tasked to rate the 6 options including the BAU scenario along pre-defined criteria. Criteria focussed on the following aspects:

- General- which required experts to rate each option in terms of its adequacy in solving waste management problems in Harare;
- Social acceptance- which required experts to rate each option in terms of preparedness of the public to co-exist with the WtE installation (in relation to the not-in-my-back-yard (NIMBY) syndrome, the willingness to separate waste and pay revised and probably higher waste collection and tipping fees in line with each option;
- Impact on health and safety-which required experts to rate each option in terms of how people’s health and safety would be generally impacted
- Local benefit- which required experts to rate each option in terms of the ability to create employment and improve the people’s livelihoods.

The scores were consolidated using simple multi-attribute rating technique adapted from Barfod & Leleur, (2014) and the results were used to evaluate the social sustainability for each option. Additionally a qualitative scale for additional benefits was included and this rated ‘Yes/No’ on whether the option is associated with the recovery of additional bi-products (digestate and compost). Additional information on the expert judgement process, selection of indicators, experts and evaluation are presented in Appendix C and results are discussed in Chapter 4.

3.5.3 Final scoring and decision

The complexity of the problem to be solved here required the application of standard decision making tools such as multi-criteria analysis (MCA), cost benefit analysis (CBA), or cost-effectiveness analysis (CEA) because the multiple criteria for evaluation being used were of a conflicting nature. One WtE option may have energy recovery technological strengths yet weak in abating emissions. Another could be superior in both yet having a very low social sustainability ranking. For these reasons, MCDA can successfully compare them and by allowing trade-off between criteria, the options can be ranked in order of their adequacy in improving Harare province's waste management system. In order to solve this complex problem and simplify the scenario evaluation process, multi-criteria decision analysis (MCDA) was used because the data set could be easily fitted into an MCA model. For this reason, a new decision model was built on 1000minds, a web-based MCDA software (Abhishek Kumar et al., 2017). The values for each scenario against the listed criteria were first calculated and fitted into an MCDA performance matrix which was directly transferred into the model on 1000minds. Values which required input data of a qualitative nature (e.g. Yes/No attributes) were also fitted into the model. The results are presented and discussed in Chapter 4.

While several MCDA software exist (including MACBETH, Visual PROMETHEE and diviz) 1000minds was preferred because of cost considerations (a free version is available for academic use). Secondly, most MCDA software requires installation on user PCs, while 1000minds is web-based and therefore relatively easier to use. Additionally, unlike PC installed MCDA software, system backup and maintenance for 1000minds is provided for free by the hosting organization which makes 1000minds a reliable tool for use. An appraisal for 1000minds indicated to be from IBM and Microsoft-sponsored contests for MCDA software read, "*In removing complexity and uncertainty from decision-making* *processes, 1000minds has blended an innovative algorithm with a simple user interface to produce a tool of great power and sheer elegance"*(1000minds, 2018).

1000minds makes use of potentially all pairwise ranking of all possible alternatives (PAPRIKA) (Abhishek Kumar et al., 2017, 1000minds, 2018). This means the model develops all potentially possible pairwise combinations between alternatives and compares them for each criterion through a series of complex functions. The model applies the 'swing weighting' technique which considers first the difference in performance of options (called alternatives in MCDA terminology) in assigning weight to each criterion and ranking the options (DET, London, 2009). At this stage, the most superior alternative can be known from the ranking. In order to make a final decision, the model is then presented to the decision makers (policy makers) who reveal their preference in terms of the relative importance of each criterion. This revises the criteria weights and gives the final ranking of options.

3.5.4 Sensitivity analysis

Sensitivity analysis in scenario modelling is normally performed by varying some assumptions, or changing some criteria or their weights (DET, London, 2009). In order to demonstrate the robustness of the model and the reliability of the results, and further guide decision making, sensitivity analysis was performed where specific preferences were assumed and the alternatives were ranked. The new rankings are critically discussed before final recommendations are given. This is provided in Chapter 4.

3.6 Summary of methodology

Table 3.2 shows a summary of the methodologies and techniques used in terms of this research and the respective resources reviewed as reference for each method.

Table 3.2 Summary of methodology

Research aspect	Specific method	Description	Main References
Assessment of flows and stocks of MSW stream. Evaluation of the effectiveness of the current waste management system	Material flow analysis	Assessment of flows and stocks of MSW stream with the objective of evaluating the effectiveness of the current waste management system and quantitatively assess problems and opportunities	Allesch & Brunner, 2017; Brunner & Rechberger, 2004; Muchangos, Akihiro, & Hanashima, 2016
MSW composition and bulk density	Coning and quartering	Sampling method in which a waste volume is separated into 4 equal parts, two of which (diagonally opposite) are selected, mixed and separated again until the desired sorting sample is selected	ASTM, 2016; EPA, Ireland, 1996
MSW proximate analysis	Thermogravimetric	Proximate values were determined by drying, weighing, high temperature decomposition and re-weighing	Boumanchar et al., 2017
MSW ultimate analysis	Organic elemental analysis (EA) and XRF-fluoro spectrometry	-A combustion technique that determines the weight percent of C, H, N,S and O - Wavelength Dispersive X-Ray Fluorescence Spectrometry	ASTM, 2013b Brown, 2011
MSW energy content analysis	Bomb calorimetry Calculation	-Direct measurement using laboratory bomb calorimeter -Estimation using empirical formulae, beginning with the modified Dulong equation	Boumanchar et al., 2017 Hosokai et al., 2016 Suthapanich, 2014
Evaluation of WtE technologies	Scenario analysis	Determining possible futuristic characteristics by using available data and subjecting it to a set of scenarios with realistic assumptions. A 10 year period (2017-2027) was assumed for the scenario modelling	(Kishita et al., 2017)
Scenario analysis:- Selection of indicators	Drawn from literature on sustainability metrics	Commonly used sustainability indicators	DET, London, 2009, Beyene et al., 2018; Kishita et al., 2017
Scenario evaluation	Scenario modelling and multi-criteria decision analysis (MCDA)	Basing on MFA results, proximate analysis results and MSW calorific value, assuming reasonable plant efficiencies. A multi-criteria analysis model was used of which the final performance was evaluated using 1000minds, a web-based MDCA software	DET, London, 2009, Beyene et al., 2018; Kishita et al., 2017)

CHAPTER 4

RESULTS & DISCUSSION

4.1 Waste management status in Harare province

The evaluation of the waste management situation for the three local authorities in the province revealed that the current waste management system is highly ineffective, characterized by an excessive build-up of waste in waste disposal areas, poor waste recovery from illegal waste heaps, a very low level of materials recycling and a high waste collection burden on local authorities. Fig 4.1 shows the consolidated mass balance table for Harare Province. The mass balance tables for individual local authorities are presented in Appendix A.

4.1.1 MSW management by individual local authority areas

4.1.1.1 Epworth

Epworth has a very small MSW throughput of only 8,078 MT/yr. A small fraction of waste generated is formally collected for disposal by the urban local authority responsible, while 79.2% of the waste generated is either buried at source or left to accumulate in the open environment in the form of illegal waste piles. The recycling rate for Epworth was found to be 0.96%. There is virtually no effort to reclaim waste from illegal dumps in Epworth. Approximately 5,700 MT/yr. of the MSW generated is either burnt or buried in shallow refuse pits thereby impacting on the quality of groundwater. Waste accumulates in formal waste disposal sites at approximately 1,600 MT/yr. and reduces slowly as the organic fraction naturally degrades.

4.1.1.2 Chitungwiza

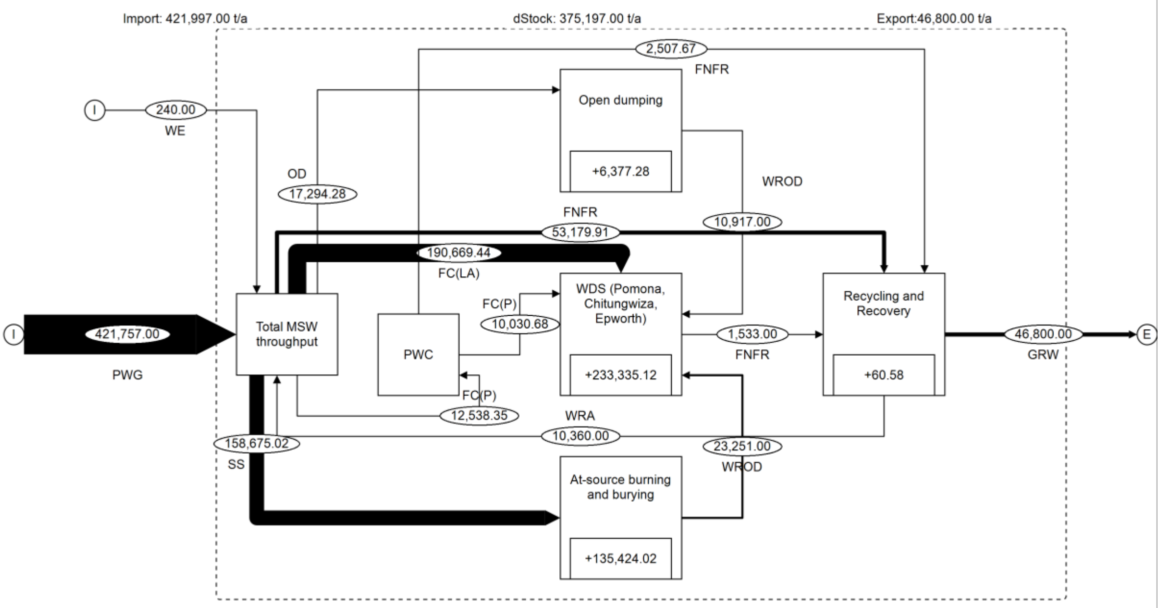
Chitungwiza has a larger MSW throughput than Epworth, with 64,800 MT/yr. In the same way, the recycling rate was obtained as 0.98%. Unlike Epworth, Chitungwiza has a high waste collection rate of 92%. The rate of formal illegal dumps clearance approaches 100%. According to the mass balance tables, a very small amount of MSW crosses the boundary from Chitungwiza into Harare under private waste collection companies. As shown, the recycling rate is still very low and there is need for improvement in order to fulfil the objectives of the ISWMP.

4.1.1.3 Harare

Of the three local authorities, Harare has the largest MSW throughput of 348,900MT/yr. The recycling rate was found to be 12.5%. MSW collection rate is below average at 44.6%. The volume of MSW buried or burnt on-site, makes up to 39% of the total waste throughput. While waste recovery from illegal open dumps is high, up to 5,000 MT of MSW still accumulates in open spaces. The MFA shows that despite having an overall larger amount of MSW to manage in comparison with either Epworth or Chitungwiza, Harare’s capacity to collect MSW is poor. In contrast to both Epworth and Chitungwiza, formal and non-formal recycling is important in affecting Harare’s MSW flow. From the information gathered during data sourcing, up to 20% of recovered MSW crosses the boundary into Harare from other cities including Bulawayo, Gweru, and Mutare, while goods processed from recycling amounting to over 40,000 MT/yr. leave the system.

4.1.2 Consolidated MFA for Harare Province

The overall per-capita MSW generation for the province was found to be 0.48 kg/cap/d which is higher than national mean of 0.37 kg/cap/d reported for a 2011 survey (EIS, 2013). This shows that Harare province is among the high MSW generators when compared to similar metropolis in other low and middle-income countries (Fig 4.2). By reason of its large MSW throughput, Harare has an obvious influence on the consolidated MSW flow for the province. Even the exceptionally high MSW collection and recovery rates for Chitungwiza are masked behind the low rates for Harare, giving an overall poor performance for the province. The overall waste collection burden on the local authorities is high, at 89%.



Harare Metropolitan Province, MSW flow, 2017

Flows [t/a]
Stocks [t]

WDS= formal solid waste disposal site;PWG=primary waste generation;GRW=recovered and recycled waste chanelled to produce new goods; WE=waste exchanged with areas outside system boundary; FC(LA)=formally collected by responsible local authority;FC(P) formally collected by private waste collectors and individuals; OD=openly dumped waste forming illegal dumps according to prevailing regulations;SS-Waste burnt and/or buried at source; FNFR=waste absorbed by formal and non-formal recycling;PWC=MSW managed by private waste collector; WROD-Waste Recovery from illegal open dumps; WRA-waste from recycling activities;

Fig. 4.1 Consolidated MFA for Harare metropolitan province

The evaluation showed that there has been virtually too little progress in achieving the goals and objectives of the ISWMP between its announcement and 2017. The quantity of waste buried or burnt at source reduced by only 1% while formal waste collection dropped by 3%. Only recycling made significant gains from 3% in 2011 to 11.1% in 2017 (effective recycling rate[4]) in which case 13.6% of the MSW had been separated for recycling (Fig. 4.3). A large proportion of MSW is still being dumped openly in the environment where it contaminates water and cause pollution. With the intermediate and final stocks of MSW accumulating up to 97% of the total MSW throughput, the lifespan of current and future landfills in Harare province is short.

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[4] The effective recycling rate is distinguished from the MSW separated for recycling. Further notes are provided in Appendix B

Additionally, the organic fraction of municipal solid waste slowly decomposes and generates GHGs chiefly methane and carbon dioxide (Kossen, 2013;Pham et al., 2015). Waste burned in the open undergoes incomplete oxidation and in the process emits considerable quantities of dioxins and related pollutants which have detrimental secondary health effects (Z. Chen et al., 2017; Nutongkaew et al., 2014; Rawn et al., 2017).

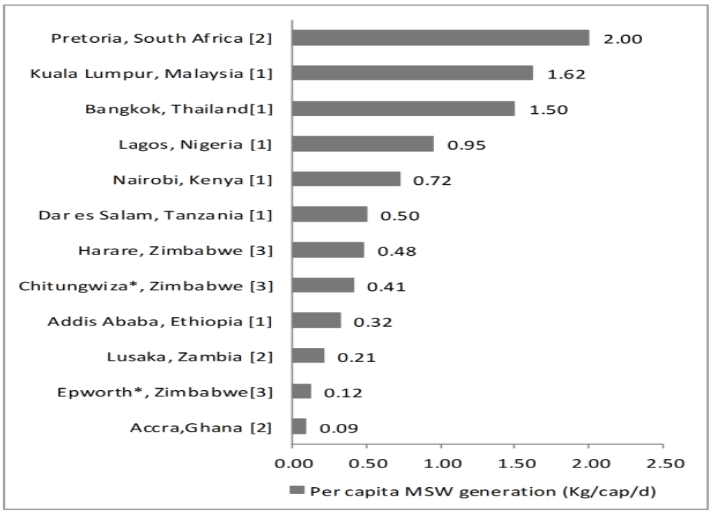
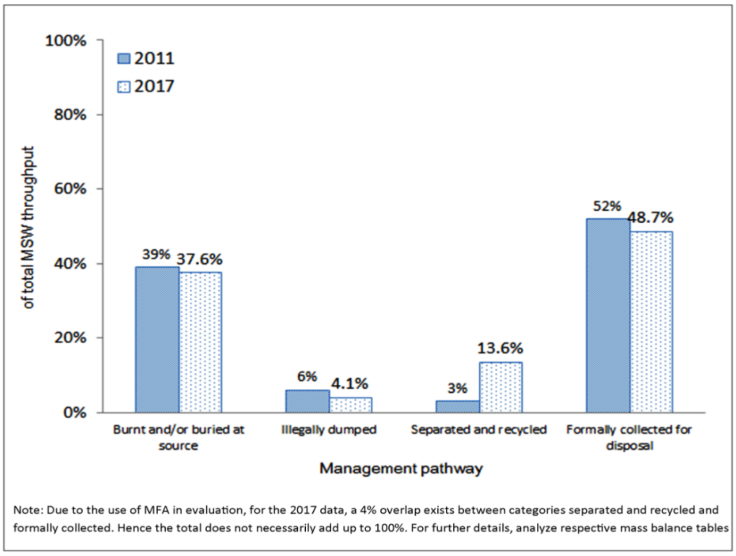


Fig. 4.2 Harare metropolitan province’s per-capita MSW generation
(As compared to 9 selected metropolitan areas in Africa and Asia.)
Data sources: [1] (Kawai & Tasaki, 2016); [2] (Rajaeifar et al., 2017);[3] current study



Note: Due to the use of MFA in evaluation, for the 2017 data, a 4% overlap exists between categories separated and recycled and formally collected. Hence the total does not necessarily add up to 100%. For further details, analyze respective mass balance tables

Fig. 4.3 Pathways taken by MSW in 2011 and 2017.

Data sources:- 2011-(IES, 2013); 2017-*current study*

Assuming that the residual waste generated between 2011 and 2017 was deposited in a new landfill, LFG emissions associated with the waste were modelled in LandGEM (version 3.02) and the results showed that the waste contributed to excessive pollution of the atmosphere (Fig 4.4). LFG emissions contain considerable quantities of GHG which works against the country's efforts to mitigate climate change. As shown in Fig 4.4, LFG emissions continue to be released even decades after waste deposits in the landfill have stopped. The LFG profile also reveals potential energy losses due to unrecovered LFG which may contain up to 50—55% methane (ATSDR, 2017).

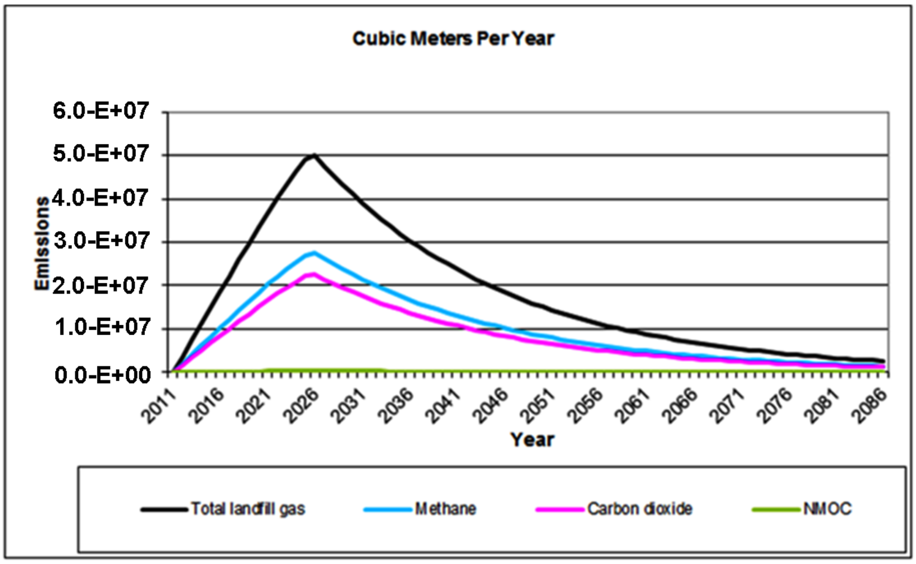


Fig. 4.4 LFG profile associated with residual waste generated between 2011 and 2017.
Source: Current study output from LandGEM V3.02

4.1.3 Waste recycling in Zimbabwe

The level of MSW recycling in the province (13.6%) when compared to the value reported in 2011 (3%) shows that there were important gains realized from intervention actions related to MSW recycling in Harare province (Table 4.1). There has been more progress in recovering paper (especially corrugated paper) than the bulk of plastics (HDPE, LDPE, PET) where over 85% of the throughput is still being sent to waste disposal sites. PETRECOZIM, a company that was set up as part of the recycling initiatives in Harare is absorbing only a small fraction of the PET throughput (Fig. 4.5). The setting up of more large scale plastic recycling centres and local markets for recycled plastic products may further the growth of waste recycling in the country.

Table 4.1 Waste recycling status for Harare province in 2017

Recyclable waste components	Estimated quantities collected for recycling (MT/yr.)	Estimated quantities available (MT/yr.)	% available for recycling
LDPE and related plastics	1,038	37,980	97.27
HDPE and PET	2,948	18,990	84.48
Corrugated paper	23,602	33,338	29.20
Mixed office paper	13,884	19,834	30.00
Ferrous and non-ferrous metals (including beverage containers)	6,794	9,706	30.00
Glass	6,120	15,614	60.80
Rubber	n/a	2,111	n/a
Total	54,386	137,573	60.47

Informal waste collectors are playing a critical role in recycling of MSW in Harare. The majority of them work at the waste disposal sites and only a few are involved in pre-disposal waste recovery. More than 500 informal waste collectors operate from Pomona dumpsite (Harare) and up to 100 operate from Chitungwiza. Two-by-two was one of the most important community based (recycling) organization (CBOs) operating from Epworth but the CBO has since stopped operations according to information provided by Epworth Local Board.

Fig. 4.5 MSW recycling in Zimbabwe

(a) Glass recovery centre in Chitungwiza, (b) A poorly kept PET drop off centre in Epworth, (c) Clear PET recycling centre in Harare, (d) Brown PET recycling centre in Harare and insert, PET chips, the major PET recycling product from Harare's PETRECOZIM

4.1.4 Opportunities for waste prevention, increased recycling and WtE recovery

Before the rest of the analyses were performed, these opportunities for waste recycling and recovery were considered in light of Zimbabwe's integrated solid waste management plan (ISWMP) which spelt out the need reduce waste, recycle waste and recover energy and materials from the waste stream. In light of that, a new MFA was drawn to reflect opportunities for waste prevention, increased recycling and WtE recovery (Fig 4.6). From the new MFA it was observed that it is possible to divert up to 200 000 MT/yr. of waste for WtE recovery without frustrating waste and recycling efforts. Appropriate interventions could also optimize utilization of biodegradable waste at-source through organic composting. This would reduce the amount of residual waste by over 50% and would lead to the clearance of illegal dumps. Waste burning and burying at source would be replaced by household OFMSW composting and produce an organic soil conditioner for peri-urban agriculture. The waste burden on the local authorities would be reduced by around 5% and recycling would increase to at least 20% as reflected in the new MFA balance table (Fig. 4.6)

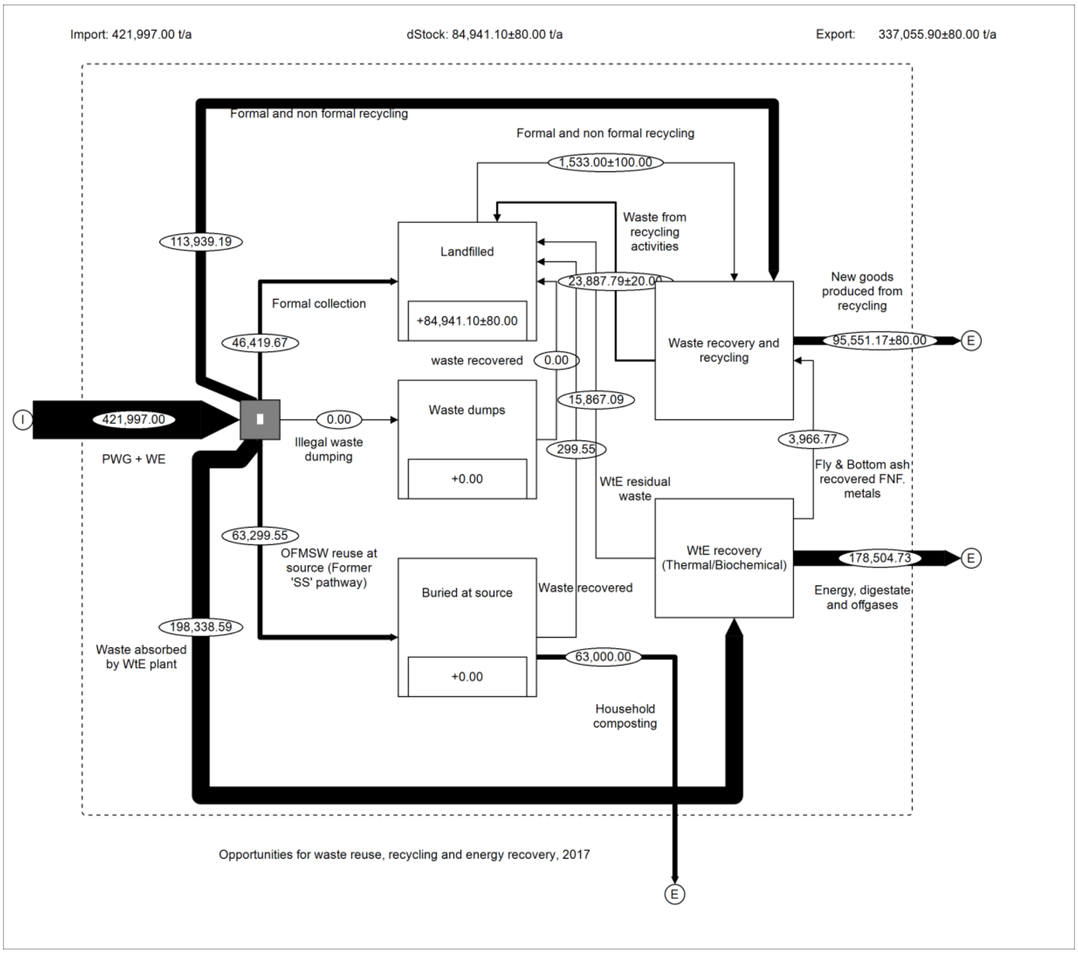


Fig. 4.6 Opportunities for waste prevention and resource recovery

Nevertheless, in order to fully understand Harare province’s potential for energy recovery and other sustainable waste management practices, more scientific data had to be gathered. This is presented in the following sections.

4.2 Physical composition

The physical composition of the waste in the three sampled areas mirrors that of most developing countries by having close to 50% of the waste being organic except for the proportion of plastics which was found to be 13.5%, which is higher than the global average for low income countries (Table 4.2) (World Bank, 2012). In energy recovery a high proportion of organics is good for biochemical WtE processes (AD, LFG to electricity, fermentation) whereas it works against thermal-based WtE recovery by giving an overall high moisture content of the waste. During the field survey, it was observed that most of the food waste was discarded in plastic bags which reduced contamination with other waste components while at the same time trapping the moisture in food waste.

Table 4.2 Physical composition of MSW in Harare Province, 2017

Category	Composition by weight (%)			Main waste items observed (arranged in order of abundance from largest to smallest)
	Harare	Chitungwiza	Epworth	
Food waste	28	40	46.4	Sadza[1] remains, vegetable remains, fruit peelings and mixtures of related food scraps
Paper	13	4	3.3	Corrugated paper, soft tissue paper, printed paper, newsprint paper, a small fraction of cardboard.
Yard waste	12	11	2.3	Fruit tree leaves, grass clippings, small twigs from ornamental plants
Sanitary waste[2]	8	10.2	5	Sanitary diapers mainly composed of wet plastic and cotton-like stuffing
Other fines	1	1.8	0.9	Mixtures of above mentioned categories of diameter less than 5mm
Plastics	21	8	11.4	Mixed packaging plastics, PET, expanded polystyrene, HDPE, thin film plastics (most plastics were soiled with food waste)
Textiles	4	2.6	1.1	Discarded clothes, cloth offcuts, hair extensions, very small fraction of leather offcuts
Rubber	1	0.4	0.1	Discarded shoe soles and mixtures of rubber offcuts
Glass	4	3	4	Beverage glass bottles, assorted broken glass
Metals	4	1	1.9	Tin cans, wires, small ferrous and non-ferrous metal items, small electronic goods
Rubble	4	18	23.6	Sand from yard sweepings, ash, pebbles, cement plaster or structure fragments

[1] Staple food for Zimbabwe and some Southern African countries made from ground corn;

[2] Category further split into plastic and textiles during sample processing

4.2.1 Changes in MSW composition between 2011 and 2017

A comparison of the waste composition from the current study with results from 2011 and 2016 studies (Table 4.3, Fig 4.7) agrees with the MFA results in that the proportion of food waste has gradually increased between 2011 and 2017 while the proportion of the recyclable components has dropped. The trend confirms the gains realised from waste recycling intervention programmes and also shows the need to develop robust initiatives targeting biogenic (especially food) waste. Table 4.3 further shows a sharp contrast between the MSW composition for Harare (2017) when compared to the national average for 2011 especially for most recyclables (metal, plastic, and paper). Most of the recycling companies operate from Harare and these data shows that they are absorbing waste from Harare more in comparison to areas outside Harare and that the level of waste recycling is lower in cities outside Harare. This is probably due to the need to minimise operating costs (especially waste transportation costs) which are reasonably higher when waste for recycling has to be moved over longer distances (Panepinto et al., 2015); C.-C. Chen & Chen, 2013)

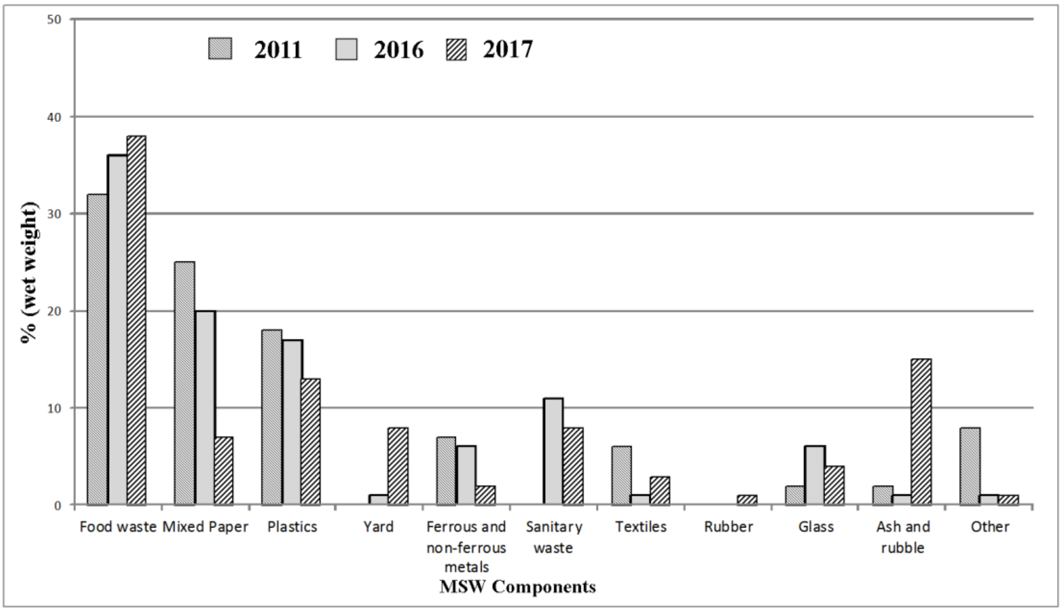


Fig. 4.7 MSW composition changes between 2011 and 2017.

Data sources: 2011 (EIS, 2013) 2016:- (EMA, 2016); 2017:-*Current study*

Table 4.3 A comparison of the MSW composition with the mean national composition in 2011

Category	% composition (wet weight)	
	Harare province (2017)[1]	National mean (2011)[2]
Food waste	38.1	32
Paper	6.8	25
Yard waste	8.4	-
Sanitary waste	7.7	0
Other fines	1.2	6
Plastics	13.5	18
Textiles	2.6	6
Rubber	0.5	-
Glass	3.7	2
Metals	2.3	7
Rubble	15.2	2
E-waste	0	2

[1] Current study

[2] Last nationwide survey (EIS, 2013)

4.2.2 OFMSW and combustible fraction

Of critical importance to the current study, was the proportion of the combustible waste and the OFMSW. These two represent what can be utilized in a typical WtE system. The results show that the OFMSW and combustible portion make up 78.7% of the MSW stream in Harare province (Table 4.4). Fig 4.8 further shows that the results for Harare are comparable to other municipalities and regions around the world where WtE has been successfully applied. The World Bank (1999) set a limit for some technologies for example incineration with energy recovery must only be considered where the combustible portion of residual waste exceeds 50 000 MT/yr. In that regards, Harare province meets the standard criteria for thermal WtE.

Table 4.4: Weight fractions of organic, combustible and incombustible waste

Sampling site	OFMSW[1] (% $_{wb}$)	Combustible non-biogenic waste (% $_{wb}$)	Incombustible, non-biogenic waste (% $_{wb}$)
Harare	41	47	12
Chitungwiza	53	25	22
Epworth	49	21	30

[1] all organic waste including food waste, yard waste and biodegradable paper

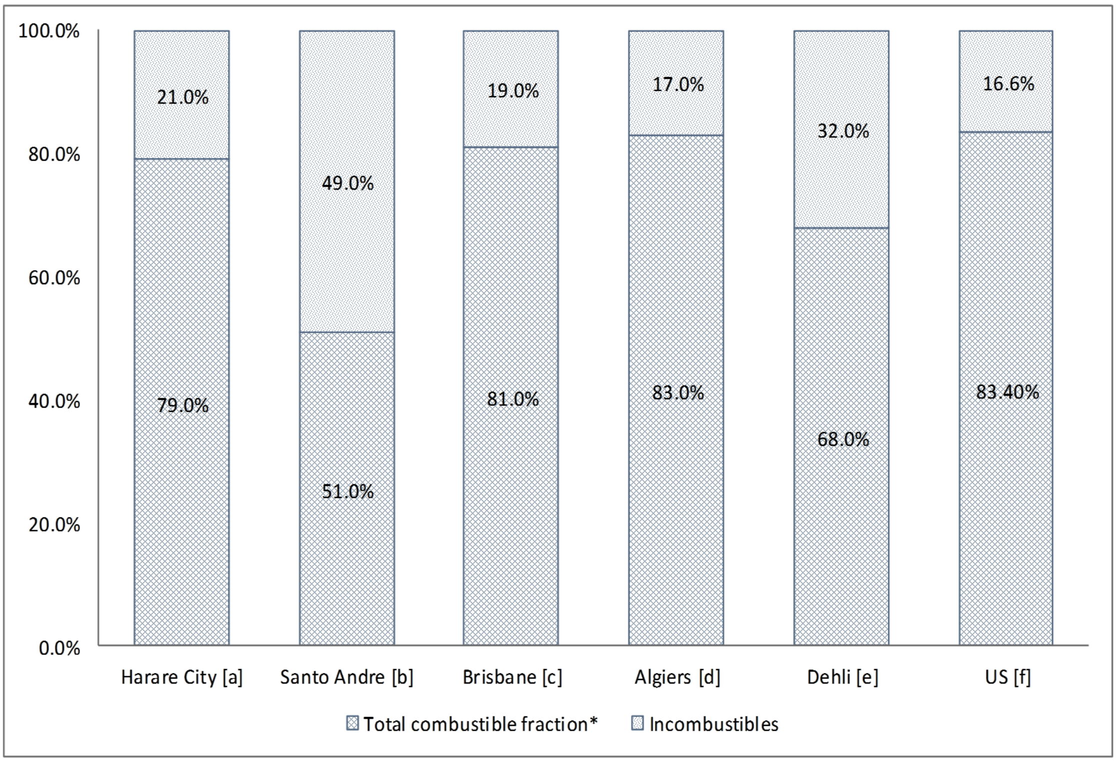


Fig. 4.8 Total combustible fraction (including OFMSW) and incombustible fraction for Harare

(As compared to 5 selected cities where similar studies have been done including the US

Data references: [a]-Current study; [b]-(Nordi, Bereche, Gallego, & Nebra, 2017); [c]-(Hla & Roberts, 2015); [d]-(Eddine & Salah, 2012); [e]-(Siddiqui et al., 2017); [f]- (EPA, 2016);(Kawai & Tasaki, 2016);(Lu, Zhang, Hai, & Lei, 2017);(Malinauskaite et al., 2017))

4.2.3 Bulk Density

The average bulk density of MSW in the province was found to be 260 kg/m^3. The bulk densities for MSW in Epworth, Chitungwiza and Harare were found to be 249.7, 265.5 and 265.8 kg/m^3 respectively. These data are useful when planning for waste storage containments such as MSW power plant offloading bays or storage bunkers and in estimating chute loading capacities (Panepinto et al., 2015). Where LFG to electricity is considered, the data will aid in determining the level of compaction necessary to achieve a balance between landfill safety and optimal microbial activity for LFG production (EPA Ireland, 1997). Additionally, the bulk density and free air space of MSW is a good indicator of its composting potential. Bulk densities of at least 350 kg/m^3 promote a good balance between moisture content and oxygen content of the composting matrix (Huerta-Pujol et al., 2010). The result for Harare City was measured on randomly selected samples which also comprised of non-compostable matter. That means bulk densities exceeding 260 kg/m^3 can be obtained when organic waste is assessed separately. While the results of the present study can serve as a general indicator of the volume of mass under composting and related space requirements, further assessments on MSW before composting is selected are recommended.

4.2.4 Moisture content as-discarded

The moisture contents (MC) for the various waste components are presented in Table 4.5. Food waste had the highest moisture content up to 70%. During the sampling exercise, the frequency of sadza, (a Zimbabwean starch thick porridge) discarded in plastic packaging was very high. The plastic bags trap the moisture inside hence despite the fact that the sampling was conducted during the dry season, food wastes still showed high moisture content. High moisture content is ideal for biochemical WtE conversion while it works against thermochemical conversion because the moisture only increases the weight of the waste without increasing the energy content (Komilis et al., 2014). This is why incineration for example has a low fuel to power efficiency between 20 and 25% (usually not more than 30%) (Beyene et al., 2018)

The overall MC for each of the three areas and the average for the province however are within acceptable limits for self-combustibility of the waste (i.e. without requiring supplementary fuel). The main reason for the overall low moisture content is the influence of the dry season during which the sampling was done. For that reason, apart from food waste discarded in plastic bags, the rest of the components had relatively lower MC levels (July-August is part of the dry season in Zimbabwe). Therefore, since the sampling period largely excluded the effect of the rainy season (November to March), except where waste storage and transfer systems prevent the ingress of rain water, higher moisture content may be recorded during the summer period. Future assessments and planning should preferably account for the effect of seasonality in MC fluctuations.

Table 4.5 Moisture content for the various waste components

	Moisture content (%)			Average moisture content for categories (%)	
Source	Harare	Chitungwiza	Epworth	Mean	SE
Food waste	70.4	71.01	68.01	70	0.9
Mixed paper	19.87	18.7	14.45	17.7	1.6
Mixed plastics	3.6	2.1	2.08	2.6	0.5
Textiles	22.8	19.8	18.7	20.4	1.2
Yard waste	41.5	32.03	21.05	31.5	5.9
Wood waste	9.98	8.67	9.09	9.2	0.4
Rubber	0.25	0.62	0.31	0.4	0.1
Other fines	32.04	21.3	21.08	24.8	3.6
Rubble and ash	3.72	2.89	2.01	2.9	0.5

	Moisture content (%)			Average moisture content for categories (%)	
Source	Harare	Chitungwiza	Epworth	Mean	SE
Other incombustibles	0.03	0.06	0.04	0.0	-
Mean[5]	30.9	36	34.4	34	-

4.3 Thermochemical characterization results

4.3.1 Proximate analysis

As has been explained in Chapter 2, volatile matter and fixed matter content of MSW are extremely crucial indicators of the oxidation potential of the MSW when used as a fuel. Normalized proximate values of moisture, ash, and combustibles (volatile matter and fixed carbon) were plotted into the Tanner diagram which is a triangle plot to show self-combustibility of the MSW without requiring supplementary fuel (Fig. 4.9). When plotted values for samples fall within the shaded region (where MC≤50%, ash≤60%, and combustibles ≥25%), it means the MSW can be used as a fuel for thermal conversion without requiring supplementary fuel (Komilis et al., 2014). As Fig. 4.9 shows, MSW from Harare City can be treated thermally without requiring additional fuel. Fig. 3 also shows how the data compares with values for other cities and regions where WtE has been successfully adopted. Values for the unsorted MSW stream normalized by taking into account separated incombustibles (assuming that this fraction has zero volatile matter and zero fixed carbon hence during combustion they will remain in bottom ash) have also been shown and they also fall within the shaded region of the Tanner diagram.

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[5] Calculated in view of respective composition for each fraction on a wet basis

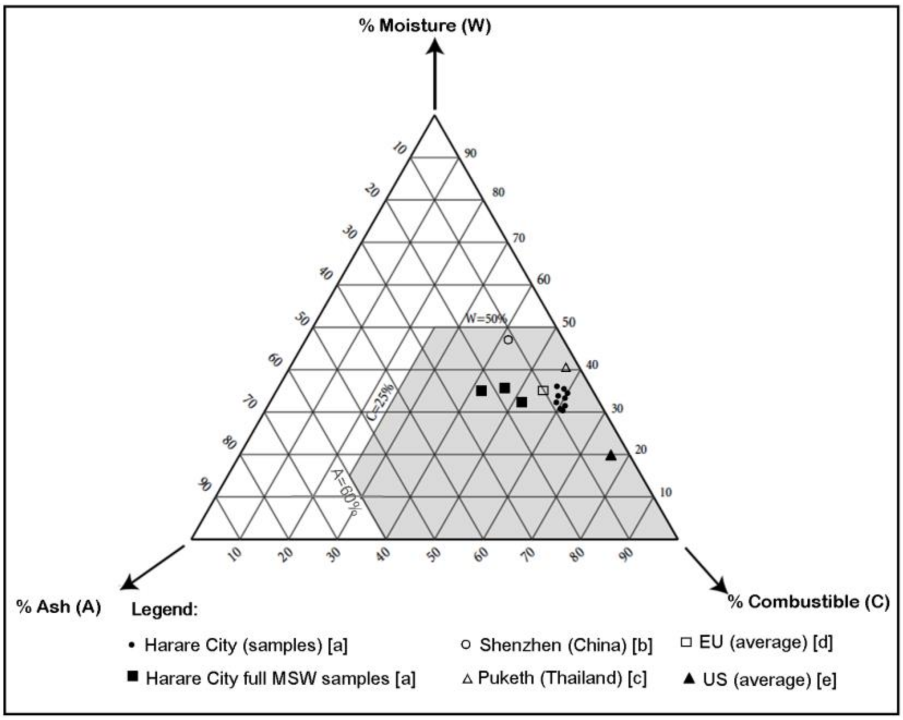

Fig. 4.9 Tanner diagram for MSW self-combustibility

Data references: [a]-current study; [b, d, e]-(Lu et al., 2017); [c]-(Suthapanich, 2014)

4.3.2 Ultimate analysis

Ultimate analysis is the determination of carbon, hydrogen, nitrogen, sulphur and oxygen as has been discussed in Chapter 2. Carbon and hydrogen represent the oxidative potential of MSW as a fuel while nitrogen and sulphur are quick pointers for the expected quality of the flue gases from thermochemical treatment (Brown, 2011). Nitrogen is also important in determination of the C/N ratio where biochemical treatment of the waste is being considered (Tanimu et al., 2014). The analyses showed high carbon composition (above 70%) for all samples (Table 4.6) which reflects high oxidative potential whether thermal or biochemical based WtE technology is selected.

Apart from providing valuable data for estimating energy content of the MSW, the values of C, H, N, S, O, and Cl are useful in predicting the nature of emissions from thermal treatment of the waste (Hla & Roberts, 2015). The results showed small concentrations of sulphur between 0.74 and 0.85% on dry basis and nitrogen values between 1.43 and 2.65%. Chlorine was also detected in the samples in the ranges of 0.42 to 0.68%. As it is generally expected of MSW thermal treatment, the possibility of flue gases containing considerable proportions of SO_2, NO_2 and chlorinated organic compounds (such as HCl) as well as dioxins and furans is certain from MSW analysed in the current study. Hence planning for thermal-based WtE recovery in Harare Province must necessarily consider installation of standard flue gas treatment systems as the possibility of acid gas formation is high. Further assessments are recommended for more detailed predictions regarding air emissions.

Table 4.6 Proximate and ultimate analysis results for Harare province

	Units[1]	Harare	Chitungwiza	Epworth	Mean for the province
Moisture content	$(\%)_{wb}$	30.9	36.0	34.4	33.77±2.61
Volatile matter	$(\%)_{db}$	79.2±0.2	84.0±0.3	82.9±0.8	82.03±2.51
Fixed carbon	$(\%)_{db}$	8.4±0.5	7.4±0.5	8.8±0.7	8.20±0.72
Ash content	$(\%)_{db}$	12.5±0.3	8.6±0.2	8.3±0.5	9.80±2.34
C	$\%_{db}$	47.12±1.27	44.62±0.36	47.86±1.18	46.50±1.70
H	$\%_{db}$	5.12±0.21	4.80±0.05	4.99±0.05	4.97±0.16
N	$\%_{db}$	1.61±0.22	2.53±0.20	2.45±0.18	2.20±0.51
S	$\%_{db}$	0.82±0.03	0.75±0.01	0.78±0.01	0.78±0.04
O	$\%_{db}$	30.90±0.21	37.32±0.37	30.84±0.39	33.02±3.72

[1] *db:-* dry basis*; wb:-* wet basis

The mean proximate and ultimate values for MSW from the three sampling sites showed a smaller variation in the elemental composition as compared to the proximate values. No previous studies could be found for Harare province in order to make a comparison for the thermochemical data hence the current study can be used as an important baseline for future assessments.

4.3.3 Energy content analysis results

The energy contents of the MSW as reported in Table 4.7 shows that the mean LHV_{wb} of the full MSW from Harare was found to be 10.1 MJ/kg by direct measurement and 9.3 MJ/kg by using the modified DuLong equation. Hosokai et al, (2016) concluded that in the energy content estimation for solid fuels, a 10% variation was acceptable for over 770 solid fuels they evaluated. This confirms therefore the result from direct measurement to be an acceptable energy content result for Harare province. The World Bank (1999) recommends a minimum of 7.0 MJ/kg for technical viability where thermochemical conversion of MSW is being considered. Therefore, the MSW for Harare metropolitan province meets this specification.

The lower heating values were higher than averages for most developing countries. The reason this must have been so is two-fold: First, the proportion of plastics, which can have energy content up to 40 MJ/kg (Zhou et al, 2015) was found to be 13.5% which is higher than the average for developing countries according to World Bank (1999). Pre-disposal removal of plastics is critically low in Zimbabwe hence a large proportion of plastics are sent to the waste disposal sites. Secondly, the sampling was conducted during a relatively drier period in Zimbabwe which lowered the moisture content levels of the wastes. For these reasons, final planning phases where thermal treatment of the waste is considered must take into account the worst case scenario where moisture content is highest and where recycling of plastic waste is optimized. Results from similar studies in selected African countries concur that while the national mean LHV for MSW can be as low as 5.0—6.0 MJ/kg, the urban centres have higher calorific values. Cases to refer include Addis Ababa, Ethiopia (12.0 MJ/kg), South Africa (7.0 MJ/kg) and Nigeria's Southern and Northern Cities (13.1 and 11.9 MJ/kg respectively)(Ogunjuyigbe, Ayodele, & Alao, 2017; REPPIE, 2017; WEC, 2016)

Table 4.7 Energy content analysis results

		Direct measurement				*Estimation*				
Category	Energy content (MJ/kg)	Hre	Chit	Epw	Mean	Hre	Chit	Epw	Mean	Agree-ment[1] (%)
Combustible portion only	$LHV_{(db)}$	22.26	18.09	21.03	20.46	18.42	16.53	18.57	17.84	87
Combustible portion only	$LHV_{(wb)}$	14.62	10.7	12.96	12.76	12.73	10.58	12.18	11.83	93
Full MSW stream	$LHV_{(wb)}$	12.87	8.34	9.07	10.09	11.2	8.25	8.52	9.32	92

[1] between mean values; Hre=Harare, Chit=Chitungwiza; Epw=Epworth

4.3.4 Ash analysis

Table 4.8 Ash analysis results for the 3 areas

	Concentration (%)on dry basis		
Compound	Epworth	Chitungwiza	Harare
MgO	0.29	0.36	0.44
Al_2O_3	0.32	0.35	0.64
SiO_2	1.37	1.65	3.15
P_2O_5	0.69	0.63	0.72
SO_3	0.4	0.4	0.48
K_2O	1.49	1.45	1.98
CaO	2.03	2.17	2.23
TiO_2	0.14	0.08	0.22
Fe_2O_3	0.35	0.4	0.71
Cl	0.42	0.57	0.68

As has been discussed under ultimate analysis, the results in Table 4.7 show that the possibility of acid gas formation and other toxic air pollutants in the flue gas during thermal waste treatment is high. This also indicates the toxicity levels associated with the waste when open refuse burning is a common practice

4.3.5 C/N ratio

The average carbon to nitrogen (C/N) ratio for Harare City as calculated from ultimate values (Table 4.6) was found to be 22.1. The C/N ratio is an important indicator where MSW is considered for anaerobic treatment. It has an ultimate control on the pH of the slurry inside the bio-reactor (Hilkiah Igoni et al., 2008;Tanimu et al., 2014). When it is too low (excessive nitrogen at the expense of carbon), there is too little substrate available for hydrolysis and hence low biogas output. When it is too high (excessive carbon at the expense of nitrogen), rapid hydrolysis will cause a sudden drop in pH and hence inhibition of pH-sensitive methanogens (Tanimu et al., 2014). The ideal C/N ratio ranges from 8 to 30 while for optimum methane production, the C/N ratio should range from 20 to 30 (Michele et al., 2015;Tanimu et al., 2014). The calculated C/N value for Harare City means the OFMSW can be digested anaerobically with minimal C/N adjustments as it is within the range of 20—30

4.4 Effect of seasonality in MSW characteristics and energy content

Waste characteristics are not static but rather dynamic (Gug, Cacciola, & Sobkowicz, 2015). One of the difficulties presented by MSW when used as a feedstock for energy recovery is its heterogeneous nature and the difficulties associated in predicting changes in MSW composition across seasons or over time (Zhou et al., 2015). The current study has shown a gradual change in MSW composition between 2011 and 2017 with biogenic waste increasing while the proportion of recyclable wastes reduced. The wet season in Zimbabwe begins from 1 November to March 31. During this period, an increase in yard wastes is expected as lawns, ornamental plants, orchard plants grow fast and will require regular trimming. Additionally, peri-urban agriculture is dominant in most of Zimbabwe's cities and this may increase the proportion of these green wastes. An increase in green waste increases the moisture content of wastes and reduces their oxidative potential. This can impact negatively on thermal WtE applications by reducing the LHV of the overall waste (Komilis et al., 2014). Across seasons, changes in moisture content are definite. The rainy season will increase the overall moisture of landfilled wastes and all waste in open receptacles and at unroofed transfer stations (for example, at Waste Away Premises). Where open refuse collection vehicles (such as tippers and tractors) are used, ingress of rain during the wet season is inevitable. During the wet season, the LHV of the waste is therefore bound to reduce and this should be investigated further. On the other hand, an increase in moisture content is good for biochemical WtE applications as higher moisture levels promote rapid breakdown of wastes. The methane generating potential of landfilled wastes increases with an increase in moisture content but excessive moisture build-up can also work against the actions of methanogenic bacteria (P. Chen et al., 2016). For these reasons, the effect of seasonality in the MSW characteristics in Harare must be consider in future assessments especially as part of the pre-feasibility studies towards WtE installations.

4.5 Scenario evaluation results

In view of the storyline for each scenario against each criterion (Section 3.5), the subsequent scenario evaluation results are presented and discussed in the following subsections. The order in which criteria were presented in Chapter 3 is not necessarily followed. Specific calculations are presented in Appendix B.

4.5.1 Energy recovery

For each scenario, the energy recovery potential was modelled by making reasonable assumptions and maintaining as much as possible conditions applicable to the study area. Since no energy recovery is applicable for the bases case or business as usual (BAU) scenario, the electrical energy output from this option is zero (0) hence the option score on the MCA performance matrix is also 0. For LFG to electricity, the LFG generating profile depicting emissions for this scenario (Fig 4.10) showed that by 2027, a total of 6.29E07 m^3 of LFG would be produced of which CH_4 is 50%. The total CH_4 yield over a 10 year period assuming a 70% LFG recovery efficiency is 2.2E07m^3 of CH_4. The electrical energy output assuming 40% conversion efficiency for a gas power engine system (Rajaeifar et al., 2017), is 85.60GWh (roughly 0.09 TWh) deliverable into the grid over the 10 year period (normalized to 8.5GWh/yr.). As Fig 4.10 shows, the peak LFG output is only attained 3 decades after the initial waste deposit at the landfill hence the 10 year LFG yield is before the period where LFG production from the landfill was at peak.

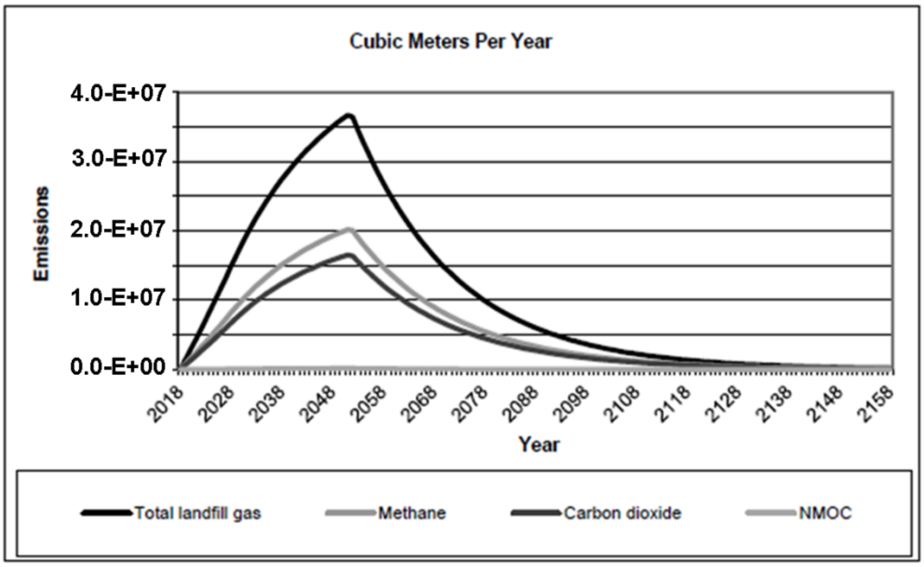

Fig. 4.10 LFG generation profile for LFG option

Source: *LandGEM model output in current study*

For the scenario AD with biogas and digestate utilization, the theoretical methane yield was calculated and found to be 2.27E07m^3. If the methane is used in a gas engine system with electrical conversion efficiency of 40%, 77.4GWh of electrical energy is deliverable into the power grid over the 10 year period (normalized to 7.7GWh per year). For the scenario MSWI with energy recovery, in view of the assumptions made in Chapter 3, over the 10 year period, this scenario has potential to deliver 560 GWh of electrical energy into the power grid (normalized to 56GWh per year).assuming 10-15% (of the gross energy yield) as the power plant energy input. Co-generation through the RDF would result in a net energy output over the 10 year period of 210.8GWh. Finally, under the Hybrid system scenario, the electrical energy deliverable into the power grid over the 10 year is therefore the sum of the energy yield from AD and MSWI, which equals 637.4 GWh (normalized to 63.7GWh per year).

Bio-chemical based WtE options would lead to lower overall energy yields in the range of 7-10 GWh/yr. while thermal technologies RDF, MSWI, and the Hybrid plant would recover 21.1 GWh, 56 GWh and 63.7 GWh per year respectively. RDF is utilizing higher calorie fuel but the energy yield is compromised as a result of the low MSW/RDF conversion efficiency and co-generation ratio ranging only 17-50% and 10-30% respectively according to best practices today (Panepinto, Blengini, & Genon, 2015).

In overall, in comparison to conventional fuels (like coal or natural gas), the competitiveness of MSW as a source of energy is low and this can lower revenue returns from energy sales. In order to make WtE profitable, this is the reason why tipping fees (which should be subsidised by the local or government authority in some cases) should be part of the revenue sources. In most developed countries tipping fees contribute up to 70% of the WtE revenue sources according to a report by the World Energy Council (WEC, 2016)

4.5.2 Total residual waste

The values for residual waste against each option or scenario are presented in Table 4.9 below. Over the 10 year period, thermo-chemical WtE technologies would lead to the greatest diversion of MSW from landfills. Under optimal waste collection rates, the quantity of landfilled waste under LFG to electricity is exactly the same under the business as usual case. This additionally meant that the LFG to electricity option leads to rapid depletion of landfill space. AD of source-separated OFMSW, MSWI, RDF and a Hybrid option would reduce the residual waste by 27%, 19%, 27% and 45% respectively.

Table 4.9 Total residual waste associated with the various scenarios

Scenario	Total residual waste (Metric tonnes)
Base Case (Business-as-usual approach)	6, 036, 959
LFG to electricity	6, 036, 959
AD with biogas and digestate utilization	4, 436, 959

Scenario	Total residual waste (Metric tonnes)
MSWI with energy recovery	4, 916, 959
RDF production for co-incineration with coal	4, 436, 959
Hybrid (AD+MSWI)	3, 316, 959

4.5.3 CH_4 and other LFG emissions from the landfill

The performance of the various scenarios against CH_4 and related LFG emissions are presented in Table 4.10 below. As a guiding principle, the results of the 2017 characterisation study were used as reference point in determining the OFMSW (47.7%) and CH_4 recovery efficiency for LFG to electricity and AD with biogas utilization were also taken into consideration (70%). In evaluating the various alternatives, their performances were compared against a common value. Detailed calculations are presented in Appendix B.

Table 4.10 Comparisons of scenarios against OFMSW in residual waste

Scenario	Residual waste (MT)	OFMSW	OFMSW as a % of total residual waste under BAU case
BAU case	6,036,959	2,879,629.44	0.48
LFG to electricity	6,036,959	863,888.83	0.14
AD with biogas and digestate utilization	4,436,959	1,279,629.44	0.21
MSWI	4,916,959	2,116,429.44	0.35
RDF for co-generation	4,436,959	2,116,429.44	0.35
Hybrid plant (AD +MSWI)	3,316,959	1,422,189.44	0.24

The residual waste associated with each scenario requires landfilling. The proportion of OFMSW present in the residual waste determines how much CH_4, CO_2 and NMOC will be generated over time. LFG option has the lowest LFG emissions associated with the residual waste since most of it will be recovered for electricity generation. Next to LFG to electricity is AD and Hybrid technology, with the proportion of biodegradable waste in the residual waste over a 10 year period being 21% and 29% respectively. MSWI and RDF will result is 35% of the residual waste being biodegradable waste. Under the business as usual case, 48% of waste in landfills over the 10 year period will be biodegradable. This means biochemical based WtE options are more effective in reducing LFG emissions associated with landfilled residual waste in comparison to thermos-chemical processes. LFG emissions from waste are important in terms of Zimbabwe's climate related goals and the choice of WtE technology here determines how much the country will benefit in this regard (GOZ, MEWC, 2014).

Even though leachate quality was not evaluated under the current study, it also follows that biochemical based WtE options would result in leachate with lower biological oxygen demand (BOD) as they are capable of recovering most of the organic matter in the waste for energy recovery. This is however a general statement which needs further scientific evaluation.

4.5.4 Avoided CO_2 emissions

For all WtE options, assuming life cycle CO_2 emissions for coal to be 1,086g/KWh (SIPA, 2017), Table 4.11 shows the avoided CO_2 emissions. Calculations are provided in Appendix B.

Table 4.11 Avoided life cycle CO_2.eq emissions for each scenario

Scenario	Normalized power output (GWh/yr.)	Avoided life cycle CO_2 emissions (tonnes CO_2.eq/yr.)
BAU case	0	0
LFG to electricity	8.5	9,231
AD with biogas and digestate utilization	7.7	8,362

Scenario	Normalized power output (GWh/yr.)	Avoided life cycle CO_2 emissions (tonnes CO_2.eq/yr.)
MSWI	56.0	60,816
RDF for co-generation	21.1	22,915
Hybrid plant (AD +MSWI)	63.7	69,178

4.5.5 Other toxic emissions

The ratings for the scenarios are presented in Table 4.12 below. WtE technologies leading to the highest energy recovery also meant the highest avoided life cycle CO_2 emissions but the benefit is offset by the highest level of toxic emissions including SO_2, NO_2, particulate matter and related flue gas pollutants which are higher for thermos-chemical based WtE options when compared to AD or LFG to electricity.

Table 4.12 Level of toxic pollutants associated with the various scenarios

Scenario	Level of other toxic emissions
Base Case (Business-as-usual approach)	n/a
LFG to electricity	Low
AD with biogas and digestate utilization	Low
MSWI with energy recovery	High
RDF production for co-incineration with coal	High
Hybrid (AD+MSWI)	Very high

4.5.6 CAPEX and OPEX

Due to unavailability of local or regional data to support an appropriate modelling tool for capital and operational expenditure, the CAPEX values were estimated on a per tonne of capacity basis based on values presented by (Aleluia & Ferrão, 2017). Operational expenditure is site specific hence literature-derived OPEX values could not be used to represent OPEX values for Harare province. For this reason, a qualitative scale was applied with three levels: low, high, and very high OPEX. CAPEX and OPEX values related to each scenario are presented in Table 4.13 below. As shown, costs are highest for thermo-chemical based scenarios and lower for bio-chemical based WtE options. They are lowest for LFG to electricity more so considering that across all scenarios, the cost of constructing a new sanitary landfill was disregarded. The Hybrid option would technically lead to the highest energy recovery albeit the high investment and operational costs.

Table 4.13 CAPEX and OPEX for the various options

Scenario	Average CAPEX estimate (Million USD)	OPEX estimate (Qualitative scale)
Base Case (Business-as-usual approach)	n/a	n/a
LFG to electricity	2.2	Low
AD with biogas and digestate utilization	4.1	High
MSWI with energy recovery	83.5	High
RDF production for co-incineration with coal	10.9	High
Hybrid (AD+MSWI)	87.6	Very high

4.5.7 Social sustainability

From the social sustainability assessment, LFG to electricity was rated as the most socially sustainable option with a sustainability score of 77.4% (Fig. 4.11). Agreement among experts was determined by means of a reliability test using SPSS. The two way mixed effects intra-class correlation coefficient was found to be 0.729 (single measures) which is sufficiently high enough to prove the reliability of the proposed decision support framework. The base case (or business-as-usual approach) was clearly rated as an unsustainable option with an overall score of 29.5%. Likewise, none of the WtE options were ranked as totally unsustainable which indicates that WtE is generally a socially sustainable option for the case under investigation.

Generally, there was preference for biochemical-based WtE options over thermal-based WtE conversion. Further analysis shows that the thermal-based options ranked poorly on health and safety impacts, confirming Zhou et al., (2017)'s conclusions that the public is still sceptical about emissions from WtE power plants. Public acceptance was the aspect that had lowest social sustainability rankings across all WtE options.

While public acceptance as a cluster indicator had a sustainability score well above 50% across all WtE options, public willingness to pay new and probably higher refuse collection fees and willingness to separate waste at-source sub-criteria scored poorly which suggests that these two may be areas of possible future conflict with the community in question. Further analysis showed that public willingness to pay new refuse collection fees was ranked below 50% of the set score (mean true score 2.44). Economic feasibility assessments normally assume raised tipping fees in order to ensure that WtE installations operate at an economically viable scale (Sudibyo et al., 2017 ; Mikic & Naunovic, 2013). The current study already shows this move may be resisted in Zimbabwe unless other measures are taken in order to educate the community about the necessity of such changes.

On the other hand, the local benefit cluster indicator which had two aspects centered on the potential ability of proposed WtE options to create employment and improve the livelihood of the local population had exceptionally high scores (mean true score above 3.50). Additional information collected from experts outside the scoring framework also brought up insights worthy of discussion. For example, informal waste recyclers (also referred to as waste pickers) felt that WtE would 'replace them' so they registered ready skepticism.

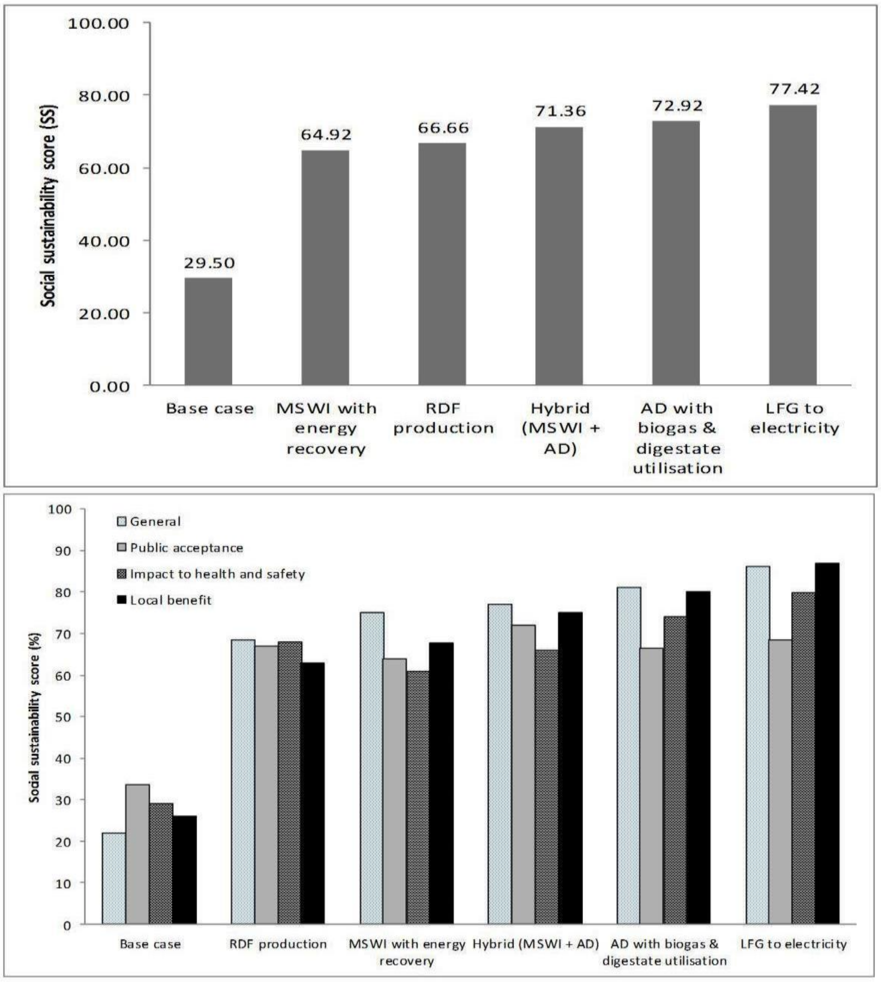

Fig. 4.11 Social sustainability ranking of the various scenarios

4.6 Final evaluation

The criteria for comparing the scenarios were many, complex and conflicting and could only be handled through the use of an appropriate multi-criteria decision analysis (MCDA) tool in determining the most sustainable course of action. After all the evaluation presented above, the results were fitted into an MCDA performance matrix as presented in Table 4.14 and Table 4.15 below. Table 4.16 shows the results after evaluation using the 1000minds software (Reference is made to Section 3.5). Fig. 4.12 shows the radar of weights which reveals the relative importance accorded to each criterion based on the swing weighting technique (Section 3.5). At this stage, the policy makers' specific preferences can be sought and incorporated into the model in order to give a final ranking of options.

Nevertheless, to further guide decision making, sensitivity analysis is performed where various preference options are considered and discussed.

Table 4.14 The preliminary performance matrix

OPTIONS	TECHNO-ECONOMIC INDICATORS			BOTH TECH/ENV	ENVIRONMENTAL INDICATORS			SOCIAL INDICATORS	
	CAPEX (US$ million - averages)[1,3]	OPEX[2,3]	Normalized energy yield (GWh/yr.)	Total residual waste over a (in Metric tonnes)	Avoided life cycle CO_2 emissions)[4] (Tonnes CO_2. eq. per yr.)	Other toxic emissions (NMOC, NO_2, SO_2 and other acid gases)	OFMSW associated with LFG emissions as a % of total residual waste for BAU scenario	Recovery of other high-value bi-products (e.g. digestate)	Social sustainability score
Base case (BAU-scenario)	0	Very low	0.00	6,036,959	0	High	0.48	No	29.50
LFG to electricity	2.2[3]	Low	8.5	6,036,959	9,231	Low	0.14	No	77.42
AD with biogas and digestate utilization	4.1	High	7.7	4,436,959	8,362	Low	0.21	Yes	72.92
MSWI	83.5	High	56.0	4,916,959	60,816	High	0.35	No	64.92
RDF for electricity co-generation	10.9	High	21.1	4,436,959	22,915	High	0.35	No	66.66
Hybrid (AD +MSWI)	87.6	Very high	63.7	3,316,959	69,178	Very high	0.24	Yes	71.36

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[1] Adapted from (Beyene et al., 2018)

[2] due to difficulties in making simulations because of unavailability of local data a scale of very low to very high was used to reflect the number of activities involved from waste collection to waste disposal of residual waste and treatment of solid, liquid and gaseous emissions. So OPEX in this context is tied to treatment capacity

[3] Each scenario is assuming that a sanitary landfill is constructed to receive residual waste, hence CAPEX for a sanitary landfill are discounted across all scenarios

[4] Avoided CO_2 emissions

Table 4.15 The final performance matrix

OPTIONS	TECHNO-ECONOMIC INDICATORS			TECH/ ENVIRONMENTAL		SOCIAL	
	CAPEX (US$ million - averages)	OPEX	Normalized energy yield (GWh/yr.)	Total residual waste over a (in Metric tonnes)	Other toxic emissions (NMOC, NO_2, SO_2 and other acid gases)	Recovery of other high-value bi-products (e.g. digestate)	Social sustainability score
Base case (BAU-scenario)	0	Very low	0.00	6,036,959	High	No	29.50
LFG to electricity	2.2	Low	8.5	6,036,959	Low	No	77.42
AD with biogas and digestate utilization	4.1	High	7.7	4,436,959	Low	Yes	72.92
MSWI	83.5	High	56.0	4,916,959	High	No	64.92
RDF for electricity co-generation	10.9	High	21.1	4,436,959	High	No	66.66
Hybrid (AD +MSWI)	87.6	Very high	63.7	3,316,959	Very high	Yes	71.36

Note: Not all criteria can be included in the MCDA performance matrix as this may result in double counting. Overlapping criteria is removed. In order to know what criteria causes double counting the question asked is, "Is there any criterion determined by another in the same performance matrix. For example, avoided CO_2 emissions are a result of energy yield hence including both of them results in double counting.

Table 4.16 The final performance matrix with direct rating[6] through PAPRIKA

Alternative/ Technology	EVALUATION CRITERIA CAPEX (million USD)	OPEX (million USD)	Normalized energy yield (GWh/yr.)	Residual waste (MT)	Level of toxic gaseous emissions (NO_2, SO_2, NMOC etc.)	Social sustainability score (%)	Additional benefits (digestate, compost)	RESULTS Rank	Mid-rank	Total score
Landfill gas (LFG) to electricity	2.2	Low	8.5	6,036,959	Low	77.4	No	1st	1	69.6%
Anaerobic digestion with biogas and digestate utilisation	4.1	High	7.7	4,436,959	Low	72.9	Yes	2nd	2	65.2%
Hybrid plant incorporating AD and Incineration with energy recovery and digestate utilization	87.6	Very high	63.7	3,316,959	Very high	71.4	Yes	3rd	3	56.5%
Refuse Derived Fuel (RDF) for electricity co-generation	10.9	High	21.1	4,436,959	High	66.7	No	4th	4	52.2%
Incineration with energy recover (electricity)	83.5	High	56.0	4,916,959	High	64.9	No	5th	5	43.5%
Business as usual case	n/a	n/a	0	6,036,959	High	29.5	No	6th	6	4.3%

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[6] This is an output from 1000minds. Refer to Section 3.5 for further details

Fig 4.12 below shows the radar of weight without the decision makers' preference as has been discussed in section 3.5.3. The diagram is an output of the model on 1000minds to show how the differences in performance of each technology option against each criterion determines the relative weight of criteria.

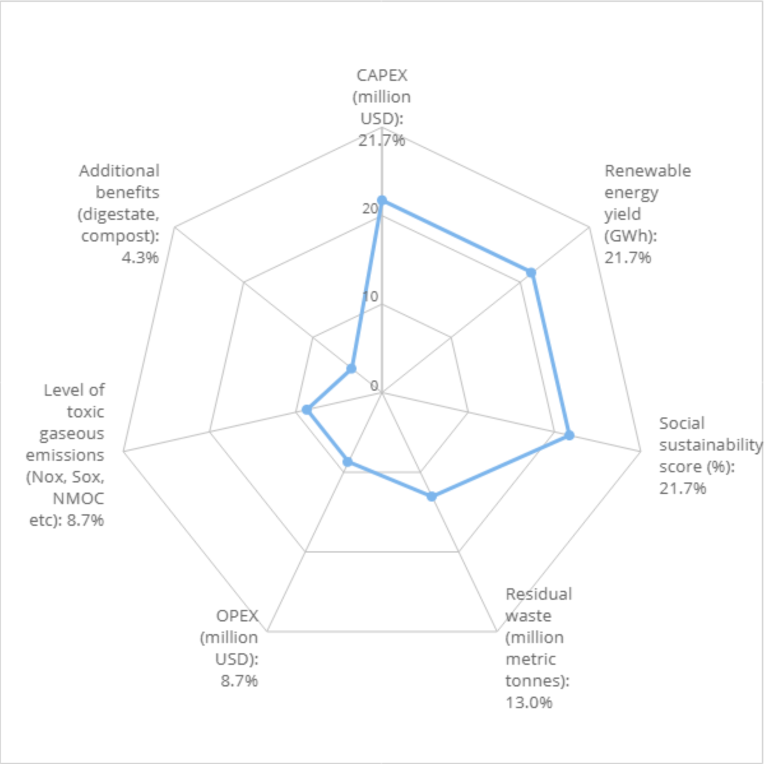

Fig. 4.12 Criteria weights without decision maker's specific preference

Note: The relative weight of criteria are defined by the 'swing weighting' technique in 1000minds MCDA model

4.7 Sensitivity analysis

Sensitivity analysis in scenario modelling is normally performed by varying some assumptions, or changing some criteria or their weights (DET, London, 2009; Abhishek Kumar et al., 2017). In the current study, sensitivity analysis was performed by tilting preferences in favor of a set of concerns over others as described below.

4.7.1 Greater concern over socio-economic factors

Sensitivity analysis was tested with the assumption that a decision is to be taken where socio-economic considerations matter the most and there is vast and inexpensive land for constructing a new sanitary landfill. Energy is useful but is not the most important factor. The situation fits best the context of Zimbabwe as a low income country even though concerns over land for constructing new landfills are beginning to increase (GOZ, 2014). Sensitivity analysis result showed that where preference is made in this way, LFG to electricity was the optimal technology of choice and thermal WtE technologies were less preferred while the business as usual remains the worst case (Table 4.17, Fig 4.13).

Table 4.17 Ranked alternatives with greater concern over socio-economic factors

Alternative	Rank	Mid-rank	Total score
Landfill gas (LFG) to electricity	1st	1	98.2%
Anaerobic digestion with biogas and digestate utilization	2nd	2	91.9%
Refuse Derived Fuel (RDF) for electricity co-generation	3rd	3	80.8%
Incineration with energy recovery (electricity)	4th	4	65.5%
Hybrid plant incorporating AD and Incineration with energy recovery and digestate utilization	5th	5	59.2%
Business as usual case	6th	6	4.9%

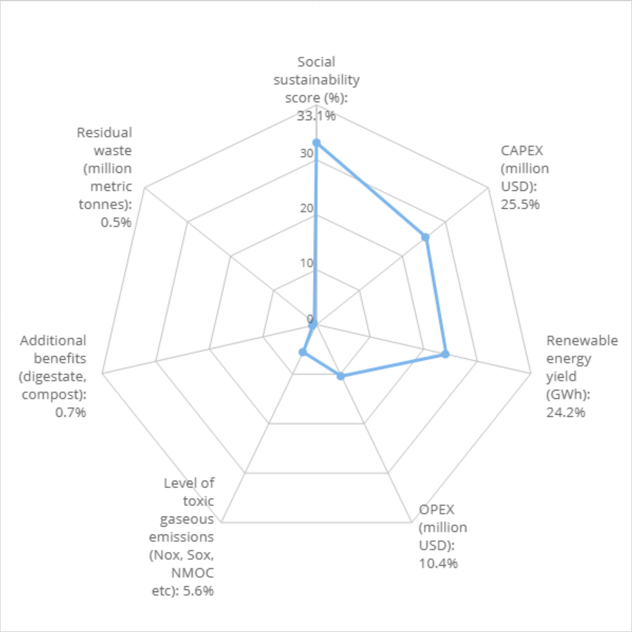

Fig. 4.13 Criteria weights where greater preference is given over socio-economic factors

4.7.2 Sensitivity analysis where there is a higher drive towards the circular economy ‘despite costs and concerns over emissions’

Sensitivity analysis was also performed where greater preference was given to optimizing waste diversion from landfill and energy recovery. Social sustainability is also important though not as much as the need to save landfill space and optimize energy recovery hence social impacts can be mitigated. Costs and concerns over emissions are of least importance. The sensitivity analysis produced a new ranking in which a hybrid plant (with AD and MSWI) was most preferred while AD and LFG to electricity were ranked second and third respectively (Table 4.18, Fig 4.14). A drive towards the circular economy despite costs and concerns over emissions is unrealistic for any country but despite so, the result showed that LFG and AD are preferred next to the Hybrid plant (which itself also incorporates AD).

Table 4.18 Ranked alternatives where least concern is given to costs and emissions

Alternative	Rank	Mid-rank	Total score
Hybrid plant incorporating AD and Incineration with energy recovery and digestate utilization	1st	1	79.1%

Alternative	Rank	Mid-rank	Total score
Anaerobic digestion with biogas and digestate utilization	2nd	2	75.9%
Landfill gas (LFG) to electricity	3rd	3	58.3%
Refuse Derived Fuel (RDF) for electricity co-generation	4th	4	56.4%
Incineration with energy recovery (electricity)	5th	5	49.8%
Business as usual case	6th	6	3.0%

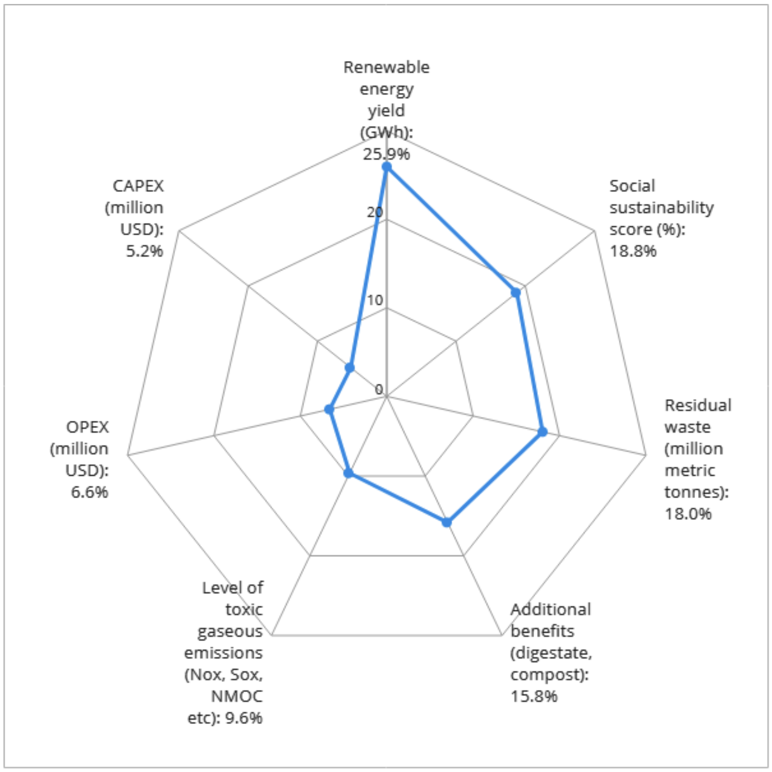

Fig. 4.14 Criteria weights-least preference for cost of alternatives and emissions

4.7.3 Sensitivity analysis where greater concern is placed over the cost of alternatives (CAPEX and OPEX)

When sensitivity analysis was performed in view of preference where greater concern was placed over the cost of alternatives as reflected by the need to lower both capital and operating costs (Fig. 4.15), LFG to electricity emerged the best option while AD was ranked the second best option (Table 4.19). This scenario fits well the context of Zimbabwe as a low income developing country where even though energy recovery is desired but budgetary concerns prevail in decision making (Schneider, Lončar, & Bogdan, 2010).

Table 4.19 Ranked alternatives where greater preference is given to cost of alternatives

Alternative	Rank	Mid-rank	Total score
Landfill gas (LFG) to electricity	1st	1	78.8%
Anaerobic digestion with biogas and digestate utilization	2nd	2	63.6%
Refuse Derived Fuel (RDF) for electricity co-generation	3rd	3	51.5%
Hybrid plant incorporating AD and Incineration with energy recovery and digestate utilization	4th	4	38.6%
Incineration with energy recovery (electricity)	5th	5	37.9%
Business as usual case	6th	6	6.1%

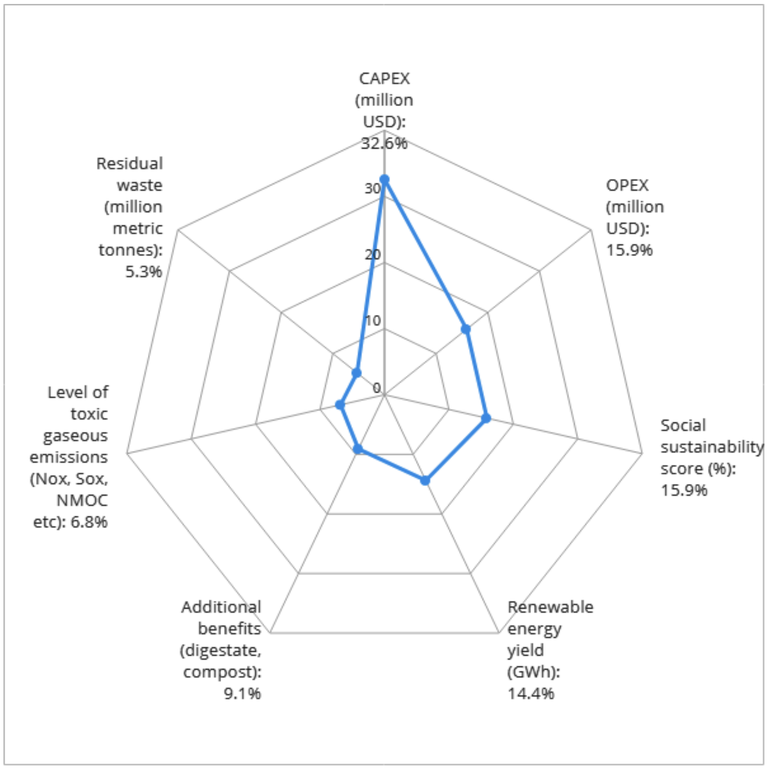

Fig. 4.15 Criteria weights where greater preference is given to cost of alternatives

4.7.4 Sensitivity analysis where greater concern is placed over environmental pollution (LFG emissions, toxic emissions)

Sensitivity analysis performed with the assumption that WtE was to be launched and concerns over toxic emissions, including those emissions associated with landfilled residual waste resulted in AD being the most preferred while LFG was ranked second (Table 4.20). During this sensitivity analysis, costs were balanced by giving highest preference to CAPEX and lowest preference to OPEX (hence in overall, cost was not the main determinant) (Fig 4.16). This scenario would fit across low-income, middle income and high-income economies where despite the need to recover energy from wastes, strict emission regulations still controls what waste management options to considered. Zimbabwe would fit into such a scenario as shown by the aims and objectives of the ISWMP and the climate response strategy (GOZ, MEWC, 2014).

Table 4.20 Ranked alternatives where greater concern is placed over environmental emissions

Alternative	Rank	Mid-rank	Total score
Anaerobic digestion with biogas and digestate utilization	1st	1	74.0%
Landfill gas (LFG) to electricity	2nd	2	73.9%
Hybrid plant incorporating AD and Incineration with energy recovery and digestate utilization	3rd	3	56.5%
Refuse Derived Fuel (RDF) for electricity co-generation	4th	4	46.1%
Incineration with energy recovery (electricity)	5th	5	34.9%
Business as usual case	6th	6	0.9%

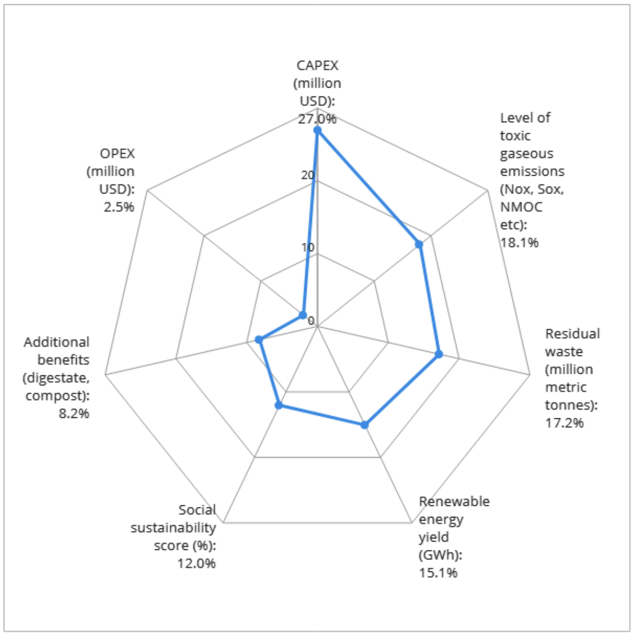

Fig. 4.16 Criteria weights where greater concern is placed over environmental emissions

4.7.5 Summary of sensitivity analysis

From the sensitivity analysis, it is evident that LFG to electricity dominated in the ranking of options except where preference was heavily tilted in favor of optimal energy recovery and optimal waste diversion without concern over the overall costs of alternatives or the emissions from WtE (Table. 4.18). Certainly, the latter does not fit a typical society with a drive towards sustainable development. Even in high income countries, modern waste management places the highest concern over costs of alternatives and the need to meet emission targets. Next in preference was AD (ranking first when environmental concerns were the most). What this implies is that LFG to electricity must be attempted first and where concerns over landfill space, residual waste, toxic emissions and the need to progress faster towards the circular economy, AD should be implemented soon after. In conclusion, sensitivity analysis proved the robustness of the initial ranking before specific preferences were made hence LFG to electricity is proven, in the context of Harare province as the alternative that guarantees optimal benefits to the waste management system.

4.8 Decision and final recommendation

The method applied in WtE technology selection in the current study adhered to a standard MCDA procedure. In that regard, the final decision is often made by policy makers who in this case represent the local authority management or at a higher level, the responsible line ministries. The technique applied has shown that LFG to electricity is the most appropriate technology in the context of Harare, Zimbabwe. Additionally, the results of sensitivity analyses have been provided to give further guidance to decision making in the various contrasting contexts. The model used in ranking options has been left open in 1000minds and can accommodate further specific decision makers' preferences in order to give the rank which is in accordance to those preferences if necessary. Nevertheless, without consideration of other unknown factors that the decision maker may choose to consider (e.g. political implications, state of the future), the ranking provided in the current study shows that the selected technology, LFG to electricity brings optimum benefits from every techno-economic, environmental and social sustainability perspective.

In the interest of the circular economy, where the objective of waste management is no longer waste disposal but to supply the economy with secondary raw materials and energy from wastes, the current study recommends therefore that LFG is installed first and AD be considered soon after.

4.9 Application of LFG to electricity in Zimbabwe

Land for constructing new landfills is beginning to be of concern to Zimbabwe especially around metropolis (Kharlamova, Mada, & Grachev, 2016). However, in the meantime, Harare needs a new sanitary landfill for a number of reasons. First, the available waste disposal sites (mainly Pomona and Chitungwiza) have been mismanaged for decades and they do not serve the objectives of modern waste management (EMA, 2016). Hence for pollution control, an engineered sanitary landfill is required. Secondly, even where other WtE technologies are to be selected, there will always be residual waste requiring safe disposal. Further, in view of the national climate related goals, reducing emissions from landfill will require a new sanitary landfill with mechanisms to collect LFG for use or flaring.

The electrical energy amounting to 9 GWh/yr. potentially recoverable from LFG to electricity can meet 0.7% of Zimbabwe's annual energy requirements for the commercial and services sector according to estimates provided by RERA-SA, (2015). While, the contribution is small, the overall environmental benefit as revealed in the current study is important.

The changes in MSW composition (discussed in Section 4.3.1) supports the idea of more intervention strategies to deal with the OFMSW (especially food waste). This is especially important for the country's climate related goals. Additionally, the MSW's C/N ratio (22.1) is ideal for methanogenic activity (in AD and LFG to electricity applications). Being a tropical country, Zimbabwe's climate is conducive for optimal microbial activity which may result in higher CH_4 yields than estimated in the current study.

Further, by opting for LFG to electricity, Zimbabwe may benefit from the regional experience. South Africa and Mauritius both SADCC countries already have successful LFG to electricity installations (WEC, 2016).

In view of this, the applicability of LFG to electricity is interesting for Zimbabwe. However, it must be emphasised that LFG to electricity requires optimal waste collection and proper landfill management which places a demand on the responsible authorities to upscale waste management operations. In the context of the circular economy, as has been recommended a quick consideration of AD soon after LFG to electricity may serve the best interests of Harare's WMS if energy recovery and waste diversion are to be optimized. The current study has demonstrated that these two technologies are the most preferred in the current context, with due consideration to technical, economic, environmental, and social sustainability.

Following up the construction of LFG to electricity with an AD plant is important in minimising residual waste and prolonging landfill lifespan which is necessary for Harare province as land for constructing new landfills is diminishing. Where LFG to electricity seems uneconomical, the already installed LFG collection system can serve in flaring in order to reduce CH_4 into CO_2, with a lower GHG potential while part of the electricity infrastructure can be salvaged for use in the AD plant. An AD plant in the form of a mechanical biological treatment (MBT) plant would serve best the interests of the circular economy in optimizing resource recovery. The costs, risks and benefits of this arrangement require further scientific inquiry.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The recovery of energy from municipal solid waste has gained popularity in many countries around the world. Zimbabwe started to have interest in waste to energy (WtE) when the new integrated solid waste management plan was announced in 2014. This had followed the realization that there were numerous problems arising from poor waste management including the proliferation of illegal waste piles (open dumps), excessive open burning of waste and exacerbated levels of littering. In 2011, the MSW national generation was around 1.65 million tonnes per year and in Harare province alone, MSW generation grew by 10.3% by the end of 2016. In order to contribute towards solving these problems, this study was undertaken over a period of sixteen months from August 2016. Many techniques were used and several kinds of analyses were performed in order to recommend the most cost-effective, environmentally sustainable and socially acceptable option that would assure optimal gains including energy recovery to Harare province’s waste management system. The major findings from the study are summarised as follows:

1) The waste management system for Harare metropolitan province was thoroughly evaluated through MFA and other techniques. The overall per-capita MSW has been found to be 0.48kg/capita per day. The waste management system is weak and in urgent need of interventions;
2) Epworth has the smallest MSW throughput of 8,078 MT/yr. The recycling rate is very low at 0.96%. The majority of waste generated (79.2%) is buried or burnt at source due to poor refuse collection by Epworth local board;

3) Chitungwiza has a higher MSW throughput (64, 800 MT/yr.) and the highest refuse collection rate in the province (92%). However, recycling is still very low at 0.98%. Illegal refuse dumps clearance is very high, exceeding 95%.
4) Harare City's MSW throughput is the largest in the province, at 348,900MT/yr. Waste collection by Harare City Council is low at 44.6%. 39% of MSW generated is either buried or burnt at source in Harare.
5) In overall, the recycling rate in the province increased from 3% in 2011 to 13.6% in 2017 showing that interventions in line with recycling recorded important gains.
6) However, the rest of the indicators show that the waste management system is not effective. Overall waste collection dropped from 52% in 2011 to 49% in 2017. 4% of the MSW in Harare province is still being dumped in the open;
7) There is potential for increasing recycling as 60% of recyclable wastes especially LDPE, HDPE and PET are still unrecovered. There has been good progress in recycling of corrugated paper with only 30% still not being recovered;
8) The MSW composition in the province shows a very high proportion of plastics (13.5%) when compared to the global average for low income countries. Chitungwiza has the highest fraction of food and yard wastes going to waste disposal sites. In overall, 78.6% of the MSW in Harare is combustible including the organic fraction (OFMSW); A comparison with 2011 and 2016 data shows that 20% of food and yard wastes generated is not reaching the waste disposal sites. This is being buried at source or discarded in the open environment where it causes pollution.
9) Between 2011 and 2017, there has been an increase in the proportion of food waste and a decline in the proportion of recyclables

10) The MSW in Harare province compares well with other metropolitan areas around the world where WtE has been successfully implemented;
11) The moisture content of the wastes ranged from 30 to 36% with the average being 34%. The average bulk density was found to be 260 kg/m^3. Proximate results showed that volatile matter ranged from 79—84%, fixed carbon ranged from 7.4—8.8% and ash content ranged from 8.3—12.5%. The evaluation showed that the MSW can be treated thermally for energy recovery without requiring supplementary fuel;
12) Elemental analysis showed that the MSW has a high oxidative potential with the average being C- 47%, H-4.9%, N-2.2%, O-33%, S-0.8%. Ash analysis revealed that thermal treatment of the waste would result in emissions containing Cl, SO_2, NO_2 and other pollutants in concentrations that warrant the installation of standard flue gas treatment systems;
13) Energy content analysis showed that the MSW in Harare province has lower heating value of 10.1 MJ/kg which is ideal for thermochemical processing according to global practices. The MSW is therefore suitable for incineration with energy recovery with minimal pre-treatment. The energy content may be lower during the rainy season.
14) Six scenarios evaluated over a 10 year period, 2017-2027 showed that it is technically possible to generate in excess of 60 000 MWh/yr. of electricity through thermal treatment. However, evaluation to find the most cost-effective, environmentally sustainable and socially acceptable WtE treatment option showed that landfill gas (LFG) to electricity can bring the optimal benefits in the current context.
15) Thermal based WtE scenarios were superior over biochemical based WtE process in energy recovery, avoided CO_2 emissions, and reduction of residual waste requiring

landfilling but weaker in economic considerations related to CAPEX and OPEX, as well as in consideration of toxic emissions such as SO_2, NO_2 and LFG emissions from landfilled residual waste.

16) While WtE was generally concluded a socially sustainable option in Zimbabwe, biochemical based options were more preferred. Thermal based WtE options ranked poorly on aspects related to safety and health which suggests that the public has a phobia for pollution associated with WtE thermal treatment.
17) LFG to electricity is the most attractive alternative and upon it other WtE technologies can be successfully developed in the future. Theoretically, in view of current global practice, approximately 9,000 MWh/yr. of electricity can be generated from LFG to electricity in Harare province under optimum waste collection rates. Next in the ranking of alternatives was anaerobic digestion. Thermal based processes were not preferred despite having the highest energy recovery potential. Other considerations like investment and operating costs and level of toxic emissions gave them poor performance in scenario evaluation;
18) The downstream benefits of having LFG to electricity installations would include approximately 9,200 tonnes of avoided life cycle $CO_{2.}$eq emissions per year by replacement assuming the energy produced could have been obtained from coal combustion;
19) Sensitivity analysis showed that LFG to electricity remains the best option in all cases fitting the context of Zimbabwe. The business as usual scenario remains the worst case;
20) As an important final recommendation in light of the circular economy, LFG should be installed first and AD be considered soon after in order to reduce the residual waste

requiring landfilling. Such an AD plant should take the form of an MBT plant in order to facilitate resource recovery, and higher waste diversion rates.

5.2 Recommendations for further study

WtE characterization studies should essentially reflect seasonal changes in waste composition (Hla & Roberts, 2015). This was not possible due to time and resource constrains and is suggested for further study before full commercialization of WtE in Zimbabwe. Additionally, scenario modelling had more than two non-numeric criteria. Sensitivity analysis showed that the model could provide the best results when all the criteria are numeric entities from quantitative analyses. Further study should explore this possibility in order to improve the reliability of the final evaluation. A full cost-effectiveness evaluation should also be done for the recommended technology. Finally, the management of sanitary waste as an emerging waste stream requires further inquiry.

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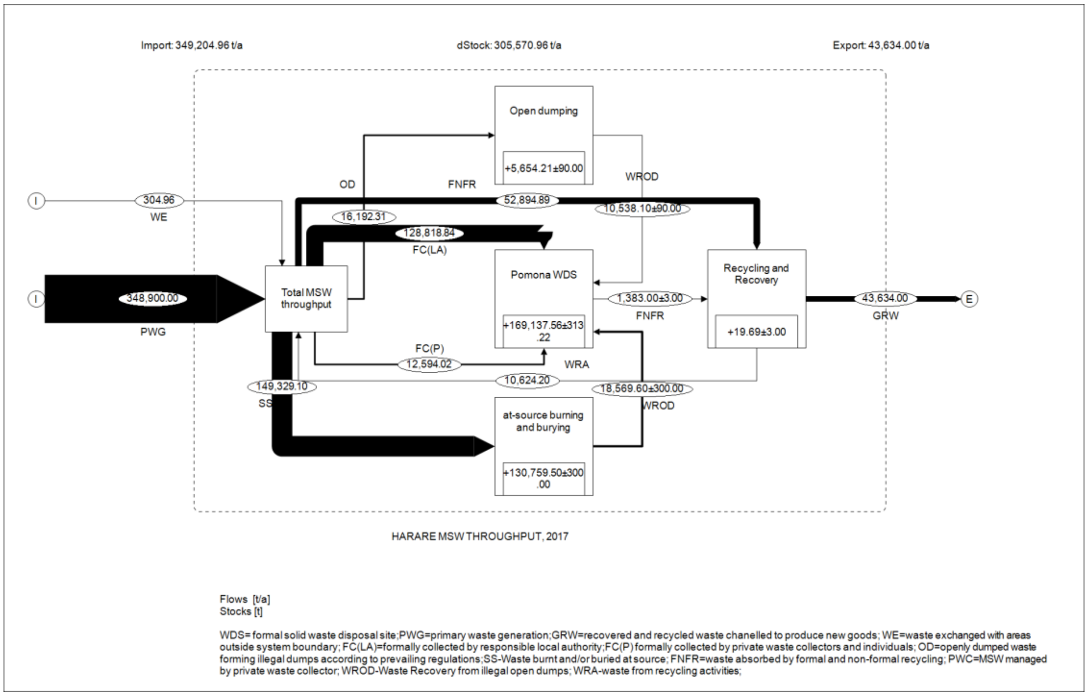
APPENDICES

APPENDIX A

ADDITIONAL MFA MASS BALANCE TABLES



WDS= formal solid waste disposal site;PWG=primary waste generation;GRW=recovered and recycled waste chanelled to produce new goods; WE=waste exchanged with areas outside system boundary; FC(LA)=formally collected by responsible local authority;FC(P) formally collected by private waste collectors and individuals; OD=openly dumped waste forming illegal dumps according to prevailing regulations;SS-Waste burnt and/or buried at source; FNFR=waste absorbed by formal and non-formal recycling; PWC=MSW managed by private waste collector; WROD-Waste Recovery from illegal open dumps; WRA-waste from recycling activities;

Fig A1 Mass balance table for MSW flow in Harare City, 2017

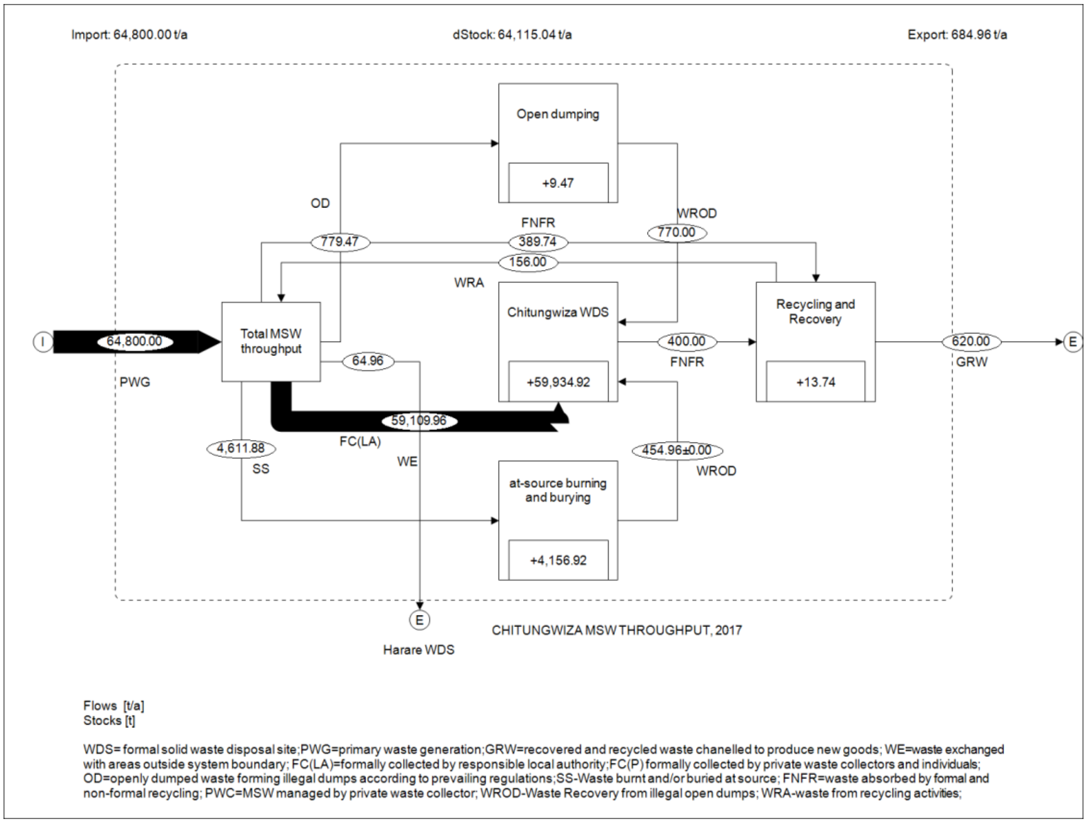


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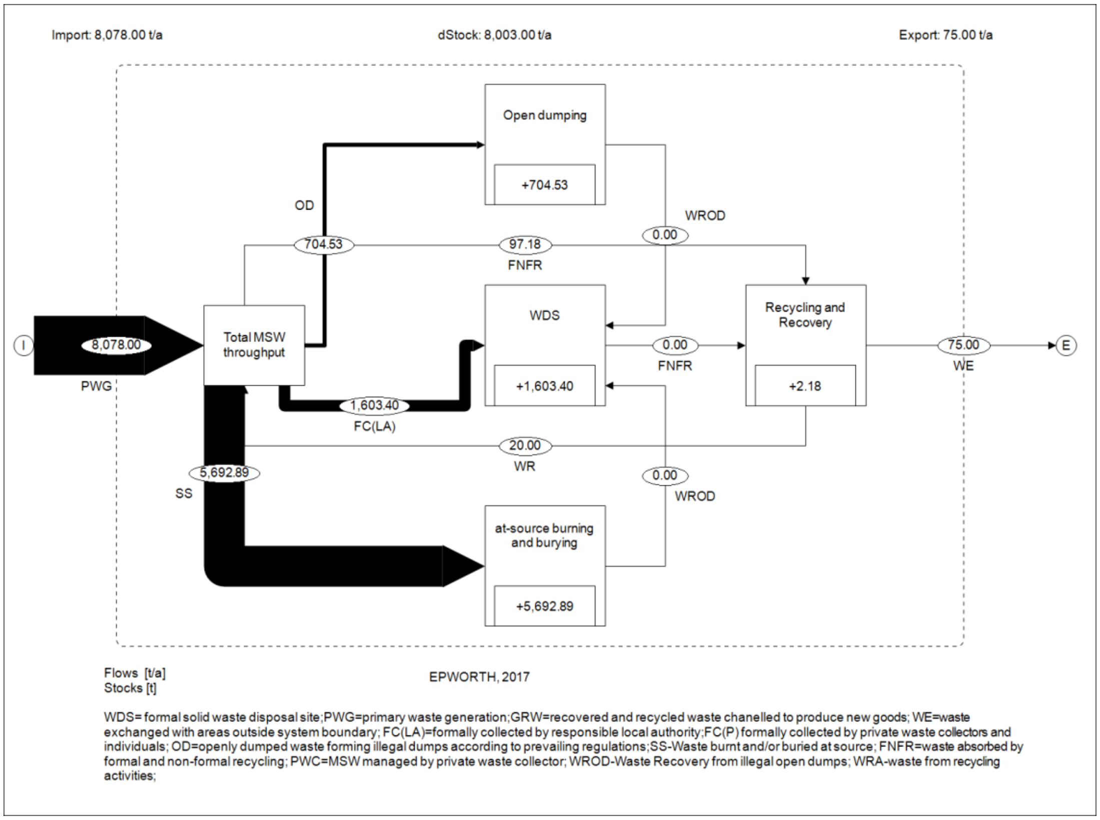
Fig A2 Mass balance table for MSW flow in Chitungwiza town, 2017



WDS= formal solid waste disposal site;PWG=primary waste generation;GRW=recovered and recycled waste chanelled to produce new goods; WE=waste exchanged with areas outside system boundary; FC(LA)=formally collected by responsible local authority;FC(P) formally collected by private waste collectors and individuals; OD=openly dumped waste forming illegal dumps according to prevailing regulations;SS-Waste burnt and/or buried at source; FNFR=waste absorbed by formal and non-formal recycling; PWC=MSW managed by private waste collector; WROD-Waste Recovery from illegal open dumps; WRA-waste from recycling activities;

Fig A3 Mass balance table for MSW flow in Epworth town, 2017

APPENDIX B

ADDITIONAL INFORMATION UNDER MATERIALS AND METHODS

B1: Additional information under evaluation of WMS using MFA

(vi) Per capita MSW generation

$$W_c \quad = \quad \frac{\sum_{k=1}^{n} PWG_k}{\sum_{k=1}^{n} Pk} \; x \; \frac{10^3}{365} \qquad \text{(B1)}$$

Where W_c is the MSW generation per capita (kg/day), *n* is the number of local authorities for which the data is being compiled, $PWG_k$is the annual MSW generation in local area *k*, in MT/yr. and $P_k$is the population in local area *k* (persons)

(vii) The effective MSW recycling rate

$$R_n \quad = \quad \frac{\left(\sum_{k=1}^{n} FNFR_k - \sum_{k=1}^{n} WRA_k\right)}{\sum_{k=1}^{n} PWG_k + WE_k} \; x \; 100 \qquad \text{(B2)}$$

Where R_n is the effective waste recycling rate (%), *n* is the number of local areas for which the data is being compiled, $FNFR_k$ is the quantity of waste absorbed by formal and non-formal recycling for local authority *k*, WRA_k is the quantity of waste produced from recycling activities in local authority *k*, PWG_k is the primary waste generation for local authority *k* and WE_k is the quantity of waste imported across local authority *k's* spatial boundary

(viii) The MSW collection efficiency

$$R_c = \frac{[FC(P) + FC(LA) + FNFR]}{PWG + WE} \; x \; 100 \qquad \text{(B3)}$$

Where R_c =is the MSW collection rate (%)

FC(P) and F(LA) = quantities of waste collected by private operators and the local authority respectively

FNFR = is the quantity of waste collected by formal and non-formal recyclers

PWG and WE = the total quantity of waste imported across the system boundary.

B2: Further notes on sample preparation and analysis

Thermogravimetric experiments and related analyses must make use of fine mixtures of prepared samples with the exclusion of incombustibles (metal, glass, rubble etc) which are irrelevant for energy recovery. In order to obtain the representative samples for use in these experiments, dried and sieved samples were reconstituted by recalculating the new mass fractions on a dry and ash free basis. That is, the new sample composition was determined with the exclusion of moisture and incombustibles by reference to the original mass composition, the moisture content for each waste component and the proportion of incombustibles as shown in Table B1 below. In the final energy content calculations, the removed incombustibles and the MC for each waste fraction were taken into account.

Table B1 Composition of reconstituted samples on dry basis

Sample source	Food waste	Paper	Yard waste	Other fines	Plastics	Textiles	Rubber	Glass	Metals	Rubble
Harare_1	28	13	12	1	23	10	1	4	4	4
Harare_2	14.5	18.2	12.2	1.2	38.7	13.5	1.7	0	0	0
Chitungwiza_1	40	4	11	2	10	11	0	3	1	18
Chitungwiza_2	27.3	7.6	17.6	3.7	23	20.8	0	0	0	0
Epworth_1	46.4	3.3	2.3	0.9	12.4	5.1	0.1	4	1.9	23.6
Epworth_2	40.6	7.7	5.0	1.9	33.2	11.3	0.3	0	0	0

Site XYZ_1=original composition on wet basis; Site XYZ_2=composition of reconstituted sample on dry basis

B3: Calculations for scenario evaluation

Primary assumptions

1. Due to rapid population expansion as projected by ZNSA, 2015 and an increase in per capita MSW generation as projected by World Bank, 2012, it is assumed that the quantity of residual waste requiring disposal (Q_d) will also increase with increasing population. The current evaluation assumes projected quantities of waste requiring disposal as presented in Table B2 below.

2. Recycling and reduction efforts are assumed to affect all scenarios uniformly and therefore are considered to be constant hence are excluded from these estimates. This is important in order to assume the worst case scenario;

3. Residual waste will be deposited in a new sanitary landfill with usable capacity 5 million metric tonnes.

4. LFG emissions are modelled using LandGEM version 3.02 at conventional landfill conditions (i.e. default values) and CH_4 content in LFG set at 55%

5. For all WTE plants the minimum capacity will be 100,000MT/yr. doubled in the 5th year. The hybrid plant shall therefore have twice as much capacity. The assumption is based on minimum scales for commercialization as provided by World Bank, 2009 and current practices as reviewed by Beyene et al, (2018)

6. In all cases, normalized electrical energy output per year ignores the assumption that capacity is doubled in the 5th year. The net electrical energy output over the 10 year period is simply divided by 10 to give a normalized figure in GWh/yr. According to assumption (5) the treatment capacity is doubled in the 5th year so the actual energy yield is lower in the first 4 years and higher in the last 6 years. This normalization was meant to enable comparisons only.

Table B2 Projected MSW requiring disposal 2017-2027

Year	Year	Projected waste after recycling and waste reduction efforts (MT)
-	2017	421,757
1	2018	443,932
2	2019	460,325
3	2020	472,128
4	2021	514,678
5	2022	562,880
6	2023	573,801
7	2024	601,223
8	2025	622,317
9	2026	651,354
10	2027	712,564

Calculating residual waste under each scenario

Determining how much residual waste will require landfilling under each scenario is based on plant capacities where MSW is diverted for treatment.

Base case or business as usual (BAU) case

No MSW is diverted for treatment. The total residual waste is the cumulative total of waste from year 1 to year 10 determined using eq. B4

$$Q_{(w-res)} = \sum_{i=1}^{n} Q_d \, i \qquad \text{(B4)}$$

Where $Q_{(w\text{-}res)}$ is quantity of waste requiring landfilling, Q_d is quantity of residual waste for year *i* (Table B1 above), and *i* is the year during which the residual waste was generated and n is the total number of years

Therefore for the BAU case, $Q_{(w\text{-}res)}$ = 6,036,959 MT

LFG to electricity

LFG to electricity does not divert waste from landfills hence $Q_{(w\text{-}res)}$ is the same for BAU case

Therefore for LFG to electricity, $Q_{(w\text{-}res)}$ = 6,036,959 MT

AD with biogas and digestate utilization, and RDF

Treatment capacity from year 1 to year 4 = 100,000MT/yr.

Treatment capacity from year 5 to year 10 = 200,000MT/yr.

Therefore total MSW diverted over 10 years = 1, 600, 000 MT hence residual waste requiring landfilling is the difference between $Q_{(w\text{-}res)}$ and MSW diverted:

$$Q_{(W-res)} = 6{,}036{,}959 - 1{,}600{,}000 \qquad \text{(B5)}$$

Therefore for AD with digestate utilization and RDF, the residual waste = 4, 436,959MT

MSWI

For MSWI treating unsorted MSW, the mass reduction is 70% and the volume reduction is 90%.according to (Beyene et al., 2018) Incombustibles (rubble, grit etc) are separated prior to combustion. Therefore the 30% residual waste fraction is taken into account as follows:

Totals treatment capacity = 1, 600, 000 MT

Residual waste from incineration = 0.3 X 1, 600, 000 MT

= 480, 000 MT

Therefore total residual waste from MSWI = 4, 436,959 + 480, 000 MT

=4,916,959MT

Hybrid Plant (AD + MSWI)

The total residual waste under a Hybrid Plant is the sum total of residual waste under AD and MSWI (taking into account 30% residual waste from MSWI as above)

Total treatment capacity = 3, 200, 000MT

Residual waste from MSWI = 480, 000MT

Therefore total residual waste = 6,036,959 – 3,200,000 + 480,000 MT

=3,316,959MT

Calculations on energy recovered

In all cases, first the electrical energy yield over the 10 year period is given in GWh. The normalized figure in GWh/yr. is for comparison purposes only (please refer to assumptions above)

Estimating energy potential for BAU scenario

Since there is no energy recovery for the BAU scenario, the energy yield is reasonably zero (0).

Estimating energy potential for LFG to electricity

Since LFG to electricity depends on decomposition of residual waste placed in the landfill, the residual waste shown in Table B1 are assumed to be the waste received into a 5million MT new landfill. The LFG modelling was performed in LandGEM V.302. The LFG yield modelled in LandGEM is 6.29E07m^3, of which 50% is CH_4. The LFG recovery efficiency is 70%. The CH_4 yield (CH_{4p}) is therefore estimated at 2.2E07m^3 assuming all applicable losses due to low efficiency

If heat was to be generated, the available fuel at STP is calculated as:

$$CH4_{fuel} = \frac{CH4_p}{22.41}\ x\ CH4\ molar\ mass \qquad \text{(B6)}$$

=16,029.26 kg CH_4

The heat yield assuming CH_4 calorific value of 55MJ/kg

=16,029.26 x 55 MJ

=889,624.14 MJ

If electricity is the output (with direct use in gas engines), the fuel to power conversion factor of 0.01MWh/m^3 CH_4 is assumed (Brown, 2011). Therefore the power output is calculated as:

$$CH4\ power\ output = 2.2E07\ (m^3) x\ 0.01\ \left(\frac{MWh}{m^3}\right) \qquad \text{(B7)}$$

=223,950MWh

In practice, the actual conversion efficiency is lower. Therefore, 40% conversion efficiency was assumed according to WEC, (2016) hence the actual power output is calculated as follows.

=223,950 MWh x 0.4

=89,580 MWh

=89.6 GWh

Assuming a 5% energy requirement (WEC, 2016), the net electrical energy output is calculated as:

=89.9 GWh x 0.95

=85.12 GWh

The normalized energy potential is therefore 8.5GWh/year

Estimating energy potential for AD plant

Assuming the conditions as described in 3.5.2(iii), i.e. VS content of 0.258 kg VS/kg OFMSW, 55% CH_4 concentration in biogas, the theoretical CH_4 yield is estimated to be 2.27E07m^3. Total waste treated over 10 years = 1, 600,000MT (1.6E09 kg)

i.e. 1.6E09 (kg OFMSW) x 0.258 kg VS/kg OFMSW) = 412, 800, 000 kg (actual VS for which biogas can be obtained). Assuming specific biogas yield to be 0.1 m^3/kg VS, gives 41,280,000 m^3 of biogas, containing 55% CH_4.

CH_4 yield= 0.55 X 41,280,000 m^3

$= \underline{2.27E07m^3}$

The gas to power conversion rate of 0.01 MWh/m^3 CH_4 and 40% conversion efficiency according to current practice is assumed and 10-15% of gross energy output is assumed as the energy requirement according to WEC, 2016. The gross energy electrical energy output for AD is calculated as:

22,740,157.44 (m^3) x 0.01 MWh/m^3

=227,401.57MWh

Assuming 40% power conversion efficiency for the gas engine, the actual energy yield is given by:

221,520.50 x 0.4 MWh

=90,960.62MWh

Assuming energy requirement for AD 15% upper limit in order to avoid overestimations (range 10-15% according to WEC, (2016) and World Bank (1999) of gross electrical energy output, the net electrical energy deliverable to the grid

=90,960.62 MWh x 0.85

=**77.3GWh (Normalized to 7.7GW/year)**

Estimating energy potential for MSWI plant

According to cited Beyene et al., (2018) the fuel to power efficiency for MSWI is 20%. A typical MSWI is expected to operate continuously for an average of 8 000hours per year. When the period of operation (h) is given in days, normally 365 days are used even though the actual annual operating duration is 8 000 hours. Assuming the plant capacity to be (d_{MT}) is MT.d.$^{-1}$, the annual capacity ($\bar{Q}_{MT}$) in MT/yr. is given by eq.B8

$$\bar{Q}_{MT} = d_{MT} \ x \ h \qquad (\text{MT.yr.}^{-1}) \qquad \text{(B8)}$$

For the MSWI plant, the annual treatment capacity is 100,000 MT doubled in the 5th year so the cumulative total (as calculated above) is 1,600,000MT

The lower heating value (LHV) of MSW is 10.1MJ/kg. Hence the theoretical energy yield ($E\Delta$) from thermal treatment of the wastes is given by eq.B9

$$E\Delta = LHV \ x \ \bar{Q}_{MT} \qquad \text{(B9)}$$

$E\Delta$= 1.62E10 MJ/yr

But this is only theoretical. In reality there are losses hence the thermal efficiency should be considered. Again, in practice, there is energy utilized by the WtE plant. So the net energy deliverable to the grid must be taken into account. The conversion factor (Ɛ) for heat to electrical energy is 3.6MJ/kWh. Assuming a thermal efficiency (ɳ) of 20%, and 0.2MWh/tonne of treatment capacity (worst case energy requirement), the actual energy yield E_ρ is be given by

$$E_\rho = E\Delta \; x \; \eta \; x \; \mathcal{E} \qquad \text{MWh} \qquad \text{(B10)}$$

= 897,778.50 MWh

=897.78 GWh

=897.78 GWh

And the net energy deliverable to the grid, is 897.78GWh-337.78GWh

=560GWh

<u>=The normalized energy potential is therefore 56.0GWh/yr.</u>

Estimating energy potential for RDF plant

Total treatment capacity over the 10 year period is 1,600,000MT. In current practice the MSW/RDF conversion rate can vary from 17-50% depending on the waste composition, moisture content. The lower limit was applied in order to avoid over-estimations. So the actual RDF yield is given by:

1,600,000MT x 0.17

=272,000MT

The energy content is calculated from the LHV on a dry basis of the combustible portion of MSW (Table 4.7) which is 20.46MJ/kg assuming a residual moisture of 20% (WEC, 2016, Staley, 2013).The LHV on a wet basis is therefore calculate as

=20.46 x 0.8 MJ/kg

=16.368MJ/kg

=16.4MJ/kg approximately.

The conversion factor (Ɛ) for heat to electrical energy is 3.6MJ/kWh. Assuming a thermal efficiency (ɳ) of 20%, =272,000, 000 (kg) x 16.4 (MJ/kg) x 0.000277778MWh/MJ

=247,822.42GWh

Assuming the upper limit energy requirement for RDF plants according to WEC, 2016, 15% of gross energy output (range is 5-15%), the net electrical energy output is calculated as:

=247.82GWh x 0.85

=210.647GWh

<u>The normalized energy potential is therefore 21.1GWh/yr.</u>

Estimating energy potential for RDF plant

The electrical energy output for the Hybrid Plant is the sum of the net electrical energy outputs for AD and MSWI since the plant capacities were maintained with the result that the Hybrid Plant has an overall capacity as the single systems.

Therefore, net electrical energy yield for RDF plant over the 10 year period is calculated as:

=560 GWh + 77.3 GWh

=637.3 GWh

<u>The normalized power output is therefore 63.7GWh/yr.</u>

Table B3: Normalized power output for each scenario

Scenario	Normalized power output (GWh/yr.)
BAU case	0
LFG to electricity	8.5
AD with biogas and digestate utilization	7.7
MSWI	56.0
RDF for co-generation	21.1
Hybrid plant (AD +MSWI)	63.7

Estimating avoided CO_2 emissions

The basis for calculating avoided CO_2 emissions was that energy produced from wastes would offset energy that could have been produced from coal. The range is 0.64-1.64kg/KWh. EPA cites 1,012 g/KWh. In this study, a more recent estimate by SIPA, (2017) is applied which is 1,086g/KWh

Therefore avoided CO_2 emissions are calculated as:

$$Avoided\ CO2.eq.emissions\ = Normalized\ power\ output\ x\ 1{,}086\ g\ CO2.eq \qquad \text{(B11)}$$

Example: LFG to electricity normalized power output is 8.5GWh per year (8,500,000 KWh/yr.)

Avoided CO_2 emissions = 8,500,000 x 1,086g CO_2 eq. per year

=9,231 tonnes CO_2.eq.per year

Calculating actual residual waste from which unrecovered LFG emissions are generated

Based on each scenario, residual waste is generated and is landfilled. The organic fraction (OFMSW) on the residual determines how much LFG will actually be emitted into the atmosphere. The basis of the calculation is the MSW composition obtained in the current study

(47.7% OFMSW). Depending on the composition of MSW diverted for treatment, the final composition of residual waste changes. Therefore to calculate the OFMSW the MSW composition of waste diverted for WtE is considered case by case as follows: Note that values in the results table were calculated by determining the OFMSW as a fraction to a common reference point. In this case, the waste residual waste under BAU case is used as a reference point in order to simplify comparisons across the scenarios.

BAU case:

No change in MSW composition is expected. Therefore the OFMSW is calculated as 0.477 X 6, 036,959= 2,879,629MT, (representing 48% of the MSW deposited in the landfill under BAU case)

LFG to electricity

Even though the quantity of residual waste is the same as that under BAU case, LFG is recovered at an efficiency of 70%. Therefore only 30% of the residual waste will contribute to unrecovered LFG emissions and the actual waste for which LFG emissions will be generated is calculated as:

=0.477 x 6,036,959 x 0.3MT

=863,888.83 MT (representing 14% of the waste deposited in the landfill under BAU case)

AD with biogas and digestate utilization

Under this scenario, 1,600,000 MT of source-separated organics will be removed from the waste. The residual waste is 4,436,959. If AD was not implemented, the organic fraction would be the same as that of the BAU case (2,879,629MT) but in this case it is less due to the WtE diversion. The actual OFMSW is calculated as:

=2,879,629 MT-1,600,000MT

=1,279,629.44MT (representing 29% of the total residual waste under BAU case)

MSWI and RDF

These two WtE processes absorb unsorted waste. After MSW diversion for MSWI and RDF, the residual waste still contains biogenic waste. For RDF, 1,600,000MT of MSW is diverted for treatment. The remaining fraction is 4,436,959 and still contains 47.7% biogenic waste. The advantage however against the BAU case is the quantity of residual waste is less. Hence the results against RDF is calculated as:

=2,116,429.44/6,036,959

Hybrid Plant

The hybrid plant is considered with the same calculations as the isolated systems (AD and MSWI).

APPENDIX C

ADDITIONAL INFORMATION ON SOCIAL SUSTAINABILITY OF WTE TECHNOLOGIES

C1. Additional notes under evaluation of social sustainability assessment for WtE Technologies

C1.1. Selection of social sustainability indicators

The model used follows traditional methods of soliciting opinions from experts and evaluating those opinions on a quantitative scale through the simple multi-attribute rating technique (SMART). The indicators were assessed and ranked in a systematic way for a decisive conclusion to be made. The indicators selected must cover all the possible areas where there is potential for conflict between the community concerned and the proposed WtE project. Additionally, there must be consensus among all the project stakeholders on the indicators to use and their ideal weights. (Vallance, Perkins, & Dixon, 2011)

1. The adequacy of the technology or option in addressing the current waste management problems, promoting waste prevention and complementing waste re-use and recycling efforts. Vallance et al.,(2011) termed this aspect ‘development sustainability’.
2. Public acceptance as reflected by the proposed technology’s compatibility with the local community’s social values and norms, the willingness to separate waste appropriate for the needs of a specific technology, pay new waste tipping fees and willingness to co-exist with a project based on a specific technology (in relation to the not-in-my-backyard (NIMBY) syndrome) Vallance et al.,(2011) classified these under ‘Bridge and maintenance sustainability’ .This reflects the willingness of a society to embrace externally-imposed change with continuity and development.
3. The impact of proposed WtE installations to public health and safety in terms of emissions (solid, liquid and gaseous wastes)

4. The local benefit to the community in terms of the ability of a WtE project to create employment and improve the local populace's livelihood.

Table C1: List of elicited and participating experts

Nature of organization	Number of organizations elicited	Experts who participated
Local authorities	3	1
Environmental regulatory authorities	2	1
Recycling companies	4	1
Private waste collectors	2	1
Community based organizations	2	1
Research and development specialists	2	2
Energy regulatory Authorities	2	1
NGOs (environmental pressure groups)	2	1
Environmental and energy consultancy companies	3	1

NB: More organizations were elicited than those that actually participated. The number of experts who participated is sufficient for an expert judgement process (Santoyo-Castelazo & Azapagic, 2014)

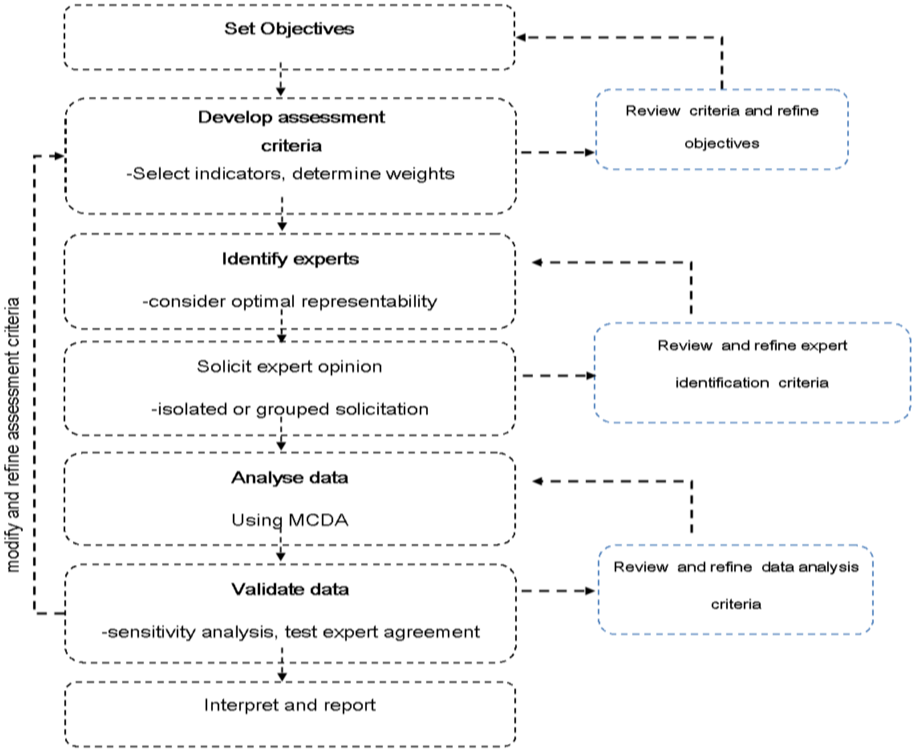


Fig. C1: The social sustainability assessment model in outline

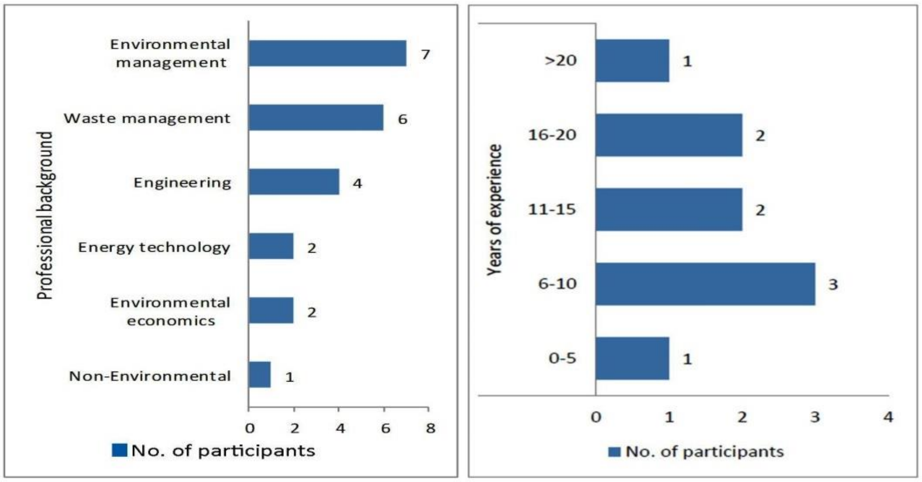


Fig. C2: Professional background and level of experience of participants (Note that some experts listed more than one professional background and the data was recorded as given)

C1.2 The simple multi-attribute rating technique (SMART)

Multi-criteria decision analysis has been used widely in research and management science to support methodologies for complex decision problems involving multiple criteria with overlapping and often conflicting goals (Barfod & Leleur, 2014). Several MCDA tools exist and in this study, SMART has been selected due to its simplicity and widespread usage (Mach, Mastrandrea, Freeman, & Field, 2017, Santoyo-Castelazo & Azapagic, 2014).

In SMART, the ratings for an alternative are assigned directly on the original scale, and by means of a value function, these ratings are converted into a common internal scale (Barfod & Leleur, 2014). The use of common scales allows for cross comparisons between different studies regardless of the natural scale used in the original rating. In the current study, the natural scale ranged 1—5, with different weights and an additive linear scale from 0—100% was selected for the final score, V(s) (eq.C.1) where:-

$$V_{(s)} = \sum_{i=1}^{I} W_i \, x \, U_{(s)} \qquad [C1]$$

Where:

$V_{(s)}$ —is the global value function representing the total sustainability score for option, '*S*'

W_i —is the weight of importance for criterion or sustainability indicator, '*i*'.

$U_{(s)}$—is the value function reflecting the performance of option, 'S' on indicator, '*i*'.

I—is the total number of sustainability indicators

The value of $U_{(s)}$ is obtained by dividing the true score awarded by the expert by the maximum possible score for that indicator. The use of a common maximum possible score across all indicators is recommended in order to maintain consistency during the scoring process

Since N experts are involved and each will give a true score which will be normalized into the sustainability score on the additive linear scale, then the mean sustainability score (SS) is given by eq.C.2, where:-

$$SS = \frac{1}{N}\, x \, \sum_{i=1}^{N} V_{(s)}(i) \qquad [C2]$$

Where SS—is the mean sustainability score for option, ‘S’

$V_{(s)}$ —is the global value function, representing the total sustainability score for option ‘S’ (and is therefore given by $V_{(s)}\,1 + V_{(s)}\,2 + V_{(s)}\,3 + \ldots + V_{(s)}\,N$)

N—is the total number of experts who scored for option, ‘S’ and $N \neq 0$;

Since the linear additive scale used in this model ranges between 0—1 (or 0—100%), the sustainability score is readily reported as a percentage.

C1.3 Sensitivity analysis

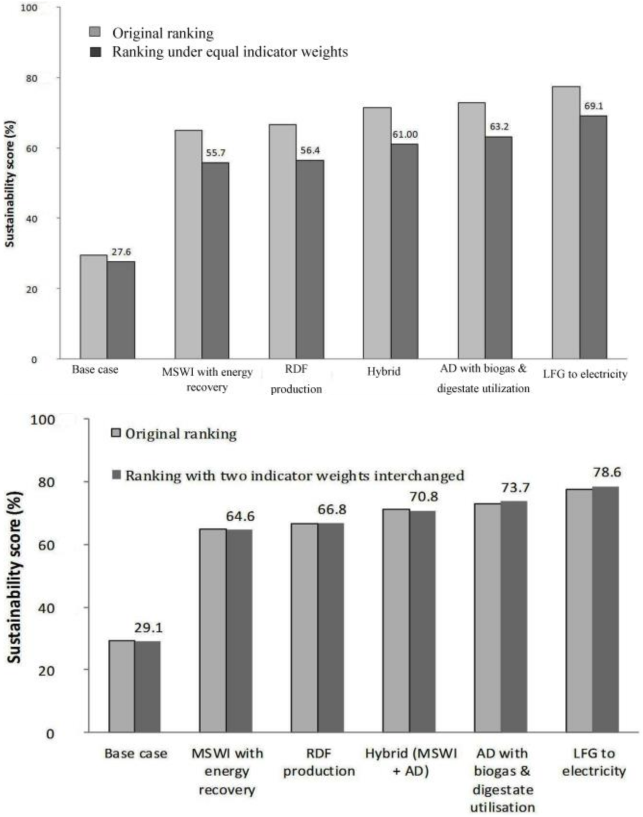


Fig. D4: Results from the sensitivity analyses

Changing weights to criteria did not affect the social sustainability ranking of options

C1.4 Structure of expert judgement score sheets

SOCIAL SUSTAINABILITY OF PROPOSED WASTE-TO-ENERGY SCENARIOS: EXPERT JUDGEMENT SCORE SHEETS

Basic information

Please kindly provide the information below. The information will not be published or shared with any 3rd parties. It is sorely for the purpose of this research

Name:

…………………………………………………………………

Email address

…………………………………………………………………

Organization and location

………………………………………………………………….

Organization's role in waste management chain (e.g. Waste generator, Waste collector, Recycling company, Research & Development, Regulator, Waste disposal company)

…………………………………………………………………

Professional expertise (e.g. civil engineering, waste management, environmental economics)

…………………………………………………………………

Years of experience

…………………………………………………………………

Introduction

….[A brief and concise introduction was given to inform experts what the study was all about and to provide information on what was expected of them]

Scenarios

Base case/Business as usual scenario

This is the Base Case scenario where a Do-nothing approach is taken. Current municipal solid waste management practices are maintained which emphasizes collection and disposal. Prevailing waste tipping fees (which are passed on to the public) are maintained.

LFG to electricity

An engineered sanitary landfill is constructed incorporating mechanisms to collect landfill gas which is upgraded and used to fire gas engines and generate electricity. The landfill receives unsorted municipal solid waste which is crudely landfilled, compacted and covered. The waste is at least 45% organic. System is designed to optimize landfill gas recovery and conversion to electricity. 70-80% of electricity produced is fed into the national grid with a Feed-in-Tariff of $0.04/Kwh above traditional supply cost. Tipping fees are increased to optimize revenue turnover. Waste is not sorted at source even though effort to recover recyclable materials is made.

Anaerobic digestion (AD) with biogas and digestate utilization

The organic fraction of municipal solid waste (estimated to be 45-55% of current MSW generation) is digested in state of the art bio-digesters and the biogas generated upgraded and directly used to fire gas engines in order to generate electricity. Residual waste is sent to the waste disposal sites. The digestate is used as a fertilizer for enriching agricultural soils. Approximately 18000MWh of electricity is produced and roughly 30,000tonnes of digestate is generated each year.70-80% of the electricity produced is sold to the grid at a FIT of $0.04 above prevailing traditional supply cost. The digestate is sold to farmers. Tipping fees are raised to optimize revenue returns

MSWI with energy recovery

Mixed municipal solid waste with an energy content of 10-12MJ/kg is combusted in state of the art incinerators and the heat captured and utilized in a heat exchanger unit to generate electricity via a combined heat and power plant. An appropriate flue gas treatment system is installed to avert air pollution from the Waste-to-energy incineration plant. The plant receives at least 70% of the mixed MSW generated in Harare metropolitan province while low energy containing residual waste and ash from the incineration plant is sent to waste disposal site. The public is encouraged to support program by separating waste at source. Tipping fees are also increased to optimize revenue returns. 70-80% of electricity produced is sold at a FIT of $0.04/Kwh above prevailing traditional supply cost.

RDF for electricity co-generation with coal

A state of the art RDF plant is installed to receive mixed MSW generated in Harare metropolitan province. Fluffy and Coarse RDF (pellets and briquettes) is produced and co-incinerated with coal in cement kilns and related applications. High moisture containing residual waste (mostly organic waste) is sent for disposal. A system is in place to ensure waste separation at source is done. Tipping fees are increased to optimize revenue returns. A system is in place to ensure the public separates waste at source to support program

Hybrid plant (AD+ MSWI)

A Hybrid system incorporating Anaerobic Digestion of the organic fraction of municipal solid waste and Incineration of the residual waste with energy recovery is installed. System is designed to optimize MSW diversion, recovery of useful materials (including ferrous and non-ferrous metals. Disposal of only inert waste materials and ash residue from incineration is done. Assumptions made for the standalone projects as in 3 and 4 are maintained.

Against each technology the experts (list shown in Table C1) were expected to independently give their judgement according to the format presented in Table C2. Score sheets were emailed to experts. Others were hand-delivered. A period of 30 days was given for all the experts to return completed score sheets after which the results were consolidated, analysed and reported.

Table C2: Expert judgement score for landfill gas to electricity

Proposed waste-to-energy technology	Brief description of scenario	Evaluation criteria	Evaluation sub-criteria	Score (1 to 5) NB: 1=worst; 5=best
1. Landfill Gas (LFG) to electricity	A properly engineered sanitary landfill is constructed incorporating mechanisms to collect landfill gas which is upgraded and used to fire gas engines and generate electricity. The landfill receives unsorted municipal solid waste which is crudely landfilled, compacted and covered. The waste is at least 45% organic. System is designed to optimize landfill gas recovery and conversion to electricity. 70-80% of electricity produced is fed into the national grid with a Feed-in-Tariff of $0.04/Kwh above traditional supply cost. Tipping fees are increased to optimize revenue turnover. Waste is not sorted at source even though effort to recover recyclable materials is made.	General	Project necessary and relevant in addressing waste management problem in Harare metropolitan province	
			Project likely to promote waste prevention	
			Project adequacy in complementing waste re-use and recycling efforts	
		Public acceptance	Project does not conflict with social values and norms	
			The public is likely to be willing to separate waste appropriate for the needs of this project	
			The public is likely to be willing to pay new (and probably higher) waste tipping fees appropriate for a project of this nature;	
			The public is likely to be willing to have a project of this nature implemented within the confines of their environment (in relation to NIMBY syndrome)	
		Impact to public safety & health	Project likely to have **NO** harmful emissions which endanger public health;	
			Project likely to have fewer negative environmental impacts than the business as usual approach	
		Local benefit	Project likely to improve livelihood of the local population	
			Project likely to create green jobs	

Additional Questions:

1. In what way would energy recovery from municipal solid waste affect your operations/work?

………

2. In your view, is Zimbabwe ready for energy recovery from Municipal Solid Wastes?

………

3. If your answer to (2) is No, what would you recommend should be done first as part of intervention strategies?

………

4. If your answer to (2) is yes, which of the 5 technologies you rated would you recommend most?

………………………………………………………………

5. Which technology would you **never** recommend for the country?

………………………………………………………………

Any additional view and comments

……

APPENDIX D

ADDITIONAL RESEARCH PHOTOGRAPHS

Plate D1: Community participation in litter cleanup activities in Harare City

Plate D2: Private company-operated waste transfer station in Harare City

Plate D3: Waste sorting during MSW characterization study in (left) Harare and (right) Chitungwiza waste disposal sites

Plate D4: Phase 1 of laboratory work at EMA laboratory, Harare, Zimbabwe

Plate D5: Appearance of MSW samples before and after thermal decomposition at 750^{o}C

Plate D6: Elemental analysis using the 2400 Series II organic Element Analyzer (Perkin Elmer)

APPENDIX E

ABSTRACTS FOR PAPERS

Table E1. Preview of papers and status

	Title	**Type**	**Status**
1	The evolution of waste-to-energy incineration: A review	Review paper	Revision under review- Renewable and Sustainable Energy Reviews
2	Hypothetical model for optimizing energy recovery from municipal solid waste thermochemical treatment through a waste separation and controlled feed (WSCF) system	Conference proceeding	Accepted for Oral Presentation at the International Conference on Sustainable Energy Management for mitigation and adaptation on Climate Change, 17 August, 2017, Siam Oriental Hotel, Hat Yai, Thailand
3	Municipal solid waste anaerobic digester designs: a review to support decision making for Harare metropolitan province	Review paper	Review made on request by EMA, Zimbabwe. Paper reviewed by a biogas expert in Denmark and presented to EMA in August 2017
4	Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision making	Research paper	Final preparation stage. Not yet submitted to journal
5	Suitability of municipal solid waste in African cities for thermochemical waste-to-energy conversion: Case of Harare, Zimbabwe	Research paper	Final preparation stage. Not yet submitted to journal

The evolution of waste-to-energy incineration: A review

Luke Makarichi* **Warangkana Jutidamrongphan** **Kua-anan Techato**

Sustainable Energy Management Research Centre, Faculty of Environmental Management, Prince of Songkla University, 15 Karnjanavanich Road, Hat Yai 90110 Songkla Thailand

HIGHLIGHTS

- The Throw Away society and the advent of waste-to-energy
- The business case of waste-to-energy
- Present concerns and future prospects

Abstract

From the simple water wall incinerators of the late 19th century, the concept of waste-to-energy incineration has evolved dramatically. Initially, waste treatment had no energy recovery objective at all. To date, state of the art facilities exist and are coupled with not only mechanisms to recover heat and energy in combined heat and power plants, but sophisticated mechanisms to clean flue gas, utilize waste water, and assimilate diverse streams of waste with high efficiency. This paper reviews the evolution of waste-to-energy incineration with the prime objective of evaluating progress made in solving problems, past and present concerns and future prospects in the industry. The review shows that waste-to-energy incineration has played a significant role in reducing the global waste problem and by maximizing its potential today, much more can be achieved. Nevertheless, the root problem which is the growing waste volume in today's society has not been fully addressed. An understanding of this evolution capacitates players in the waste-to-energy industry to better understand problems and formulate practical solutions which will steer the waste to energy incineration towards more growth in the interim and devise lasting solutions for the distant future.

Key Words: Waste-to-energy[7] (WtE), waste management, incineration, municipal solid waste (MSW)

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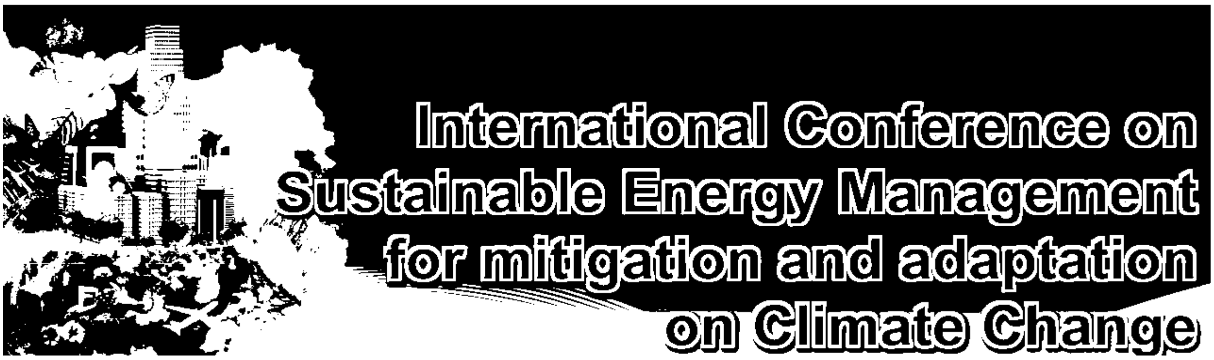
[7] While waste-to-energy also refers to conversion by biochemical processes, in this paper the term will primarily refer to waste-to-energy via incineration



Paper ID: 10

Topic: **Hypothetical model for optimizing energy recovery from municipal solid waste thermochemical treatment through a waste separation and controlled feed (WSCF) system.**

Authors[a]: Luke Makarichi*, Warangkana Jutidamrongphan, Kua-anan Techato

Affiliation:
[a]*Faculty of Environmental Management, Princes of Songkla University, Thailand*

Abstract

The popularity of waste-to-energy conversion involving municipal solid waste (MSW) has been increasing over the years. Municipal diversion for thermochemical or biochemical conversion is not only a proven waste management method, but also a means of generating energy in the form of heat or electricity to supplement traditional supplies. Unfortunately MSW's low heating value in comparison to other fuels works negatively against effective combustion. This paper proposes a hypothetical model for optimizing energy recovery from MSW thermochemical conversion through waste separation and controlled feed. A hypothetical city is assumed for which secondary data on MSW volumes and composition is used to build this model. Results show that it is possible to compute for any given area the ideal ratio at which MSW energy content is highest and feedstock quantity is guaranteed. The hypothetical model is useful in improving MSW combustion and enhancing the overall performance of a WtE system.

Keywords: Municipal solid waste (MSW), heating value, waste composition, waste to energy (WtE)

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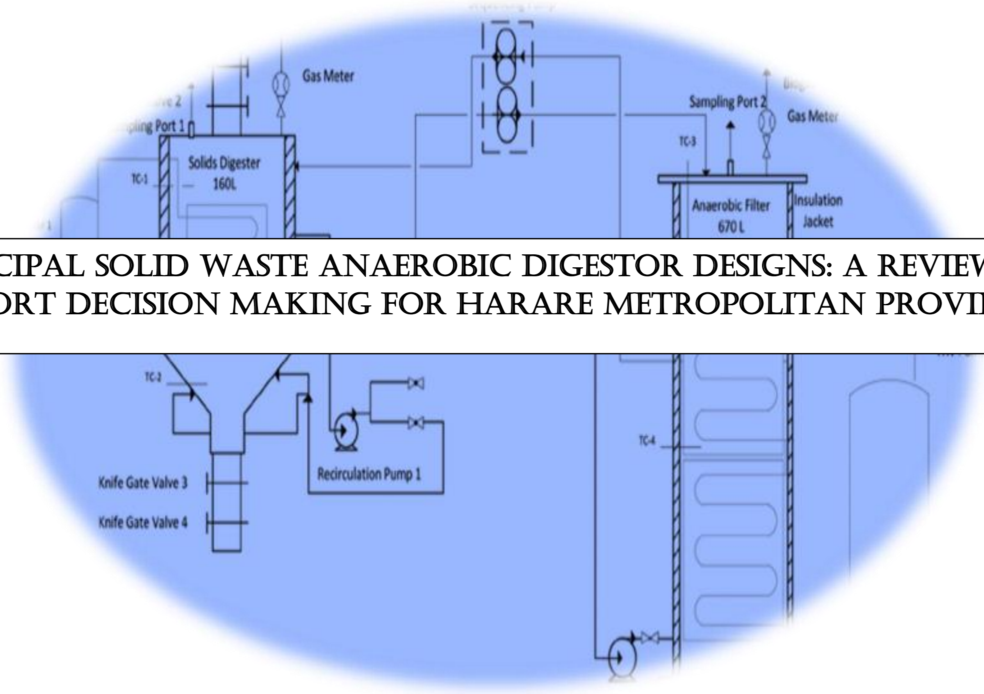
MUNICIPAL SOLID WASTE ANAEROBIC DIGESTOR DESIGNS: A REVIEW TO SUPPORT DECISION MAKING FOR HARARE METROPOLITAN PROVINCE



Luke Makarichi[8], Warangkana Jutidamrongphan (PhD.)[9] and Kua-anan Techato (PhD.)[10]

Peer reviewed in Denmark by Lars Moller[11] (PhD.)

A review prepared as part of research to support decision making and industrial development for Environmental Management Agency, Zimbabwe

Abstract

Anaerobic digestion (AD) of municipal solid waste (MSW) is a mature, commercially viable and well proven technology for treating municipal solid waste with the added advantage of recovering materials, energy in the form of biogas and a soil conditioning digestate. Bio-digester designs for the organic fractions of municipal solid waste are diverse. The choice of which design to install, or which add-on features to incorporate depends on a

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[10] Associate Professor and program chairman, Sustainable Energy Management, Prince of Songkla University, Hat Yai, Songkhla, Thailand

[11] External reviewer, Denmark

number of factors, primarily the goals or objectives of the municipal waste treatment, the physical and chemical characteristics of the solid waste, intended use of products and bi-products of the project as well as the available investment capital. Systems can be classified in terms of operational criteria (continuous versus batch), total solids content (low solids or wet systems versus high solids or dry systems), number of steps making up the whole AD process (Single AD systems versus Double and Multiple AD systems) and operating temperature (Mesophiic~35^{o}C versus thermophilic~55^{o}C). Each design has advantages and disadvantages and most have now been improved to process high volumes of MSW with high biogas yield ranging from 0.1 to 0.2 m^3/kg VS. The biogas produced can be used as raw heating fuel or further upgraded and used in gas engines to produce electricity and heat and as a transport fuel for vehicles equipped with engines that can use compressed natural gas. In light of the MSW generated in Harare metropolitan province, preliminary studies show that 53% of the MSW is organic. This means that the province has potential to supply 233 690 tonnes of OFMSW per year. If all of this is treated anaerobically, 8,225,900 m^3 of biogas can be produced assuming 35.2% volatile solids content in the OFMSW. This can yield 4,524,245m^3 of methane (assuming 55% CH_4 content in biogas). This has a total energy content of 179,709 MJ and can fire a gas engine at 40% conversion efficiency to produce approximately 18,000MWh[12] electricity per year. The residual waste heat can be used to generate steam useful for various industries in Harare and Chitungwiza. Additionally, the process would yield approximately 35,000 tonnes per year of digestate which is a high nutrient organic fertilizer. The MSW diverted from the traditional collection and disposal route can lengthen the lifespan of current and future landfills while at the same time being used as a feedstock to produce a renewable fuel, methane which is also a greenhouse gas that would have otherwise been released from solid waste disposal sites. This review highlights MSW anaerobic digester designs as a general guide to assist in decision making for the Environmental Management Agency, Zimbabwe. A simulation was also made to estimate the biogas potential of Harare metropolitan province.

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[12] Average consumption in Zimbabwe is 60-70KWh per person/ year

Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision making

Luke Makarichi[1] Kua-anan Techato[2, 3] Warangkana Jutidamrongphan[2, 3*]

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[2] *Environmental Assessment and Technology for Hazardous Waste Faculty of Environmental Management, Prince of Songkla University, Hatyai, Songkhla, Thailand*
[3] *Center of Excellence on Hazardous Substance Management)HSM(, Bangkok, Thailand*

Abstract

When a waste management system has been evaluated and rated ineffective, there is impetus to decide on sound corrective action. Intervention actions often take the form of new policies, programs, or new capital-intensive projects which may have far-reaching implications on the welfare of societies. For this reason, decision making around these intervention actions must make use of tools designed to handle complex decisions involving multiple and often conflicting criteria, for example multi-criteria decision analysis (MCDA). In this paper, material flow analysis (MFA) is presented as a support tool prior to a full MCDA. In the adopted approach, MFA plays the critical role of evaluating the effectiveness of a waste management system and assessing the degree of improvement the proposed solutions may provide. A case study based on a practical situation in Zimbabwe is used to illustrate this relationship between MFA and MCDA. Data for the MFA were collected through literature reviews, direct field measurement and interviews with stakeholders in the waste management chain. A number of techniques were applied in the subsequent analyses, including scenario modelling. The evaluation concluded the case area's waste management system to be weak, and revealed that promoting household composting of organic waste, increasing MSW recycling to 19% and initiating medium-capacity anaerobic digestion with energy recovery and digestate utilization can lead to optimal improvement on the waste management system. The study demonstrates the value MFA can add to waste management decision making where MCDA is involved.

Key words **:**waste management; material flow analysis)MFA(; multi-criteria decision analysis; municipal solid waste)MSW(; local authority

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Suitability of municipal solid waste in African cities for thermochemical waste-to-energy conversion: Case of Harare, Zimbabwe

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Abstract

The recovery of energy from municipal solid waste (MSW) has gained popularity in many industrialized countries but its adoption in economically developing countries especially in Africa has been slow. While capital investments and technical requirements for waste-to-energy (WtE) systems are among the most important causes for this slow adoption, the unavailability of data pertaining to the thermochemical quality of MSW as a potential feedstock for energy recovery is also limiting. In this paper Harare, a typical African city is selected for a case study. The MSW was sampled, sorted and analyzed for thermochemical properties including energy content. Proximate and ultimate analyses were performed directly on reconstituted samples of the combustible portion and energy content was estimated by calculation using empirical formulae. Results show that the quality of the MSW is comparable to that in cities and regions outside Africa where WtE has been a success. The combustible fraction exceeded 75% of the MSW stream, and the MSW had an average calorific value of 10.1 $MJ.kg^{-1}$ and average moisture content of 34%, making it ideal for thermochemical treatment without requiring supplementary fuel. At the local level, the study compliments Zimbabwe's efforts in recovering energy from wastes while regionally and beyond, the paper provides a stimulus for WtE adoption in similar economically developing countries.

Key Words:

Municipal solid waste (MSW); waste-to-energy; MSW characterisation; waste management; energy content; African cities

APPENDIX F

VITAE

VITAE

Name ……Makarichi Luke………

Student ID …….591092004………………

Educational Attainment

Degree	**Name of Institution**	**Year of Graduation**
Bachelor of Science (Hon) Degree in Environmental Science and Health	National University of Science and Technology (NUST) (Zimbabwe)	2007

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List of Publication and Proceeding (If Possible)

………………………………………………………………………………………