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Research Article

Evaluation of energy generation potential from municipal solid waste in the North-West province, South Africa

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Abstract. Municipal Solid Waste (MSW) management is rapidly becoming a severe environmental problem worldwide. Developing countries, especially African cities, are the most affected due to inadequate resources to cope with increasing magnitude and complexity of the waste generated as well as the scarcity of land for disposal. As such, strategies which include waste- to-energy (WtE) generation to recover the potent energy from municipal waste could be a better option. This study sought to determine the sustainability of WtE projects for energy access to off-grid residents in the North-West province, South Africa. The study used a quantitative research design coupled with field observations and measurement of elements of the waste chain to generate primary data sets. The information was supplemented by secondary datasets on waste information and waste management at local municipalities. Results revealed that some of the classes of waste have the optimum calorific values and moisture content for WtE. The eligibility of a waste class to be used in WtE generation projects is dependent on the quantities generated. The results also indicate that using paper as fuel in the 240 tonnes/day WtE technology would cover more days of operation than plastics and rubber. Based on the 2020 estimated waste quantities, paper would last 234 days of generating about 6,944 GWh while plastics would last 177 days with energy output of 5, 207 GWh. Waste quantities generated in the North-West province could contribute to sustainable energy access to the off-grid informal settlement residents and advance waste management options through WtE. This study contributes to the literature on renewable energy and waste management in the context of green energy in South Africa.

Keywords: Calorific values; Informal settlements; moisture content; waste classification; waste-to-energy

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1. Introduction

Most developed countries have adopted a hierarchical approach to solid waste management, which states that first of all, waste should be reduced; otherwise reused or recycled, incinerated for energy recovery and, only if nothing else works, landfilled (Dijkgraaf and Vollebergh 2004; Lombardi *et al.* 2015) Despite adopting the hierarchical approach, waste is still regarded by many as a nuisance due to its polluting effects of the air, soil and water (Tabasová *et al.* 2012). However, municipal solid waste (MSW) has potential value to provide some environmental, energetic, economic, and social benefits (Ayodele *et al.,* 2018). The use of waste material as an input to produce a new product is called recycling especially the non-degradable (fossil fuel based) components such as glass, ceramics, plastic, rubber, and metal (Ayodele *et al.,* 2017).

1.1. MSW Recycling and Potentials

Recycling of waste involves separation of waste from the waste chain and processing them as products or raw materials (Coyle, 2015). In this process, wastes materials are collected either from the source or final disposal site (landfills) and separated (sorted) according to type, compressed to reduce their volume, packed, and transported to intermediate dealers or directly to the recycling plant where they enter again into the manufacturing chain (Lino and Ismail, 2017) to produce secondary materials or new products. Recycling of waste is an income generator for some communities through employment and the sale of collected MSW to buy-back centres or directly to waste treatment facilities by the waste reclaimers (Godfrey, *et al.,* 2012).

However, successful recycling programs start with potentially enabling mechanisms to collect the recyclable materials. The specific recycling program requires vigilance, active participation and sharing responsibilities from state bodies, municipalities, regions, private-owned recycling companies as well as conscious and informed participation and motivation by citizens in order to achieve the set national recycling goals (Tsimnadis et al., 2023). In South Africa, the rate of recyclable collection is low at less than 10% (Green Cape, 2015). Available data suggests that the South African informal sector is responsible for the collection of 80–90% (by weight) of the post-consumer paper and packaging recyclables (Godfrey and Oelofse, 2017). At present, there is an obvious absence of formal recycling of municipal waste whereby recyclable materials are collected by informal waste reclaimers. The waste

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reclaimers (also known as waste pickers/scavengers) collect recyclable materials both from street bins, dumpsites, and the landfills. Depending on the recyclable material collected, the waste reclaimers sell them at buy-back centres most of which are privately owned retail outlets where the waste is sorted further, treated, and compacted in readiness to be transported for manufacturing new products (DEA, 2012). Though the informal waste sector is perceived as unregulated, it is the more comprehensive and efficient than it is first taken to be because the collectors collect every recyclable piece of waste that they see in order to earn a living (Chi *et al*., 2011). In other words, recycling offers direct employment; indirect employment from the supply and demand chain of recycling businesses along with the environmental and health benefits (Liu et al., 2020). The study by Liu et al revealed that the economic benefit of paper waste recycling in 2017 in China was 458.3 yuan/ton. As such, Ayodele et al. (2018) advocates for an inclusive policy that recognises informal sector in the waste management and recycling with the view to increasing the recycling rates. At the peak of recycling is the production of usable products like building materials, composite, and energy recovery (Bocken 2016).

Energy recovery from waste combines production of heat and power. The heat can be used for generating electricity and producing drinking water through thermal desalination (Papargyropoulou *et al.* 2015). Generating energy from waste can be done through incineration, anaerobic digestion, and landfill gas recovery etc. The interest of this study is on the generation of electricity through incineration of waste, where energy is recovered in a process called waste-to-energy (WtE) (Rand *et al.* 2000; Antonopoulos *et al.* 2014). Incineration is the most common WtE method which takes place between 750 ℃ to 1,000 ℃. The plants consist of thermal part, heat recovery block and a system for cleaning of generated flue gas (off-gas in this case) (Tabasová *et al.* 2012).

During the WtE generation process, the combustible waste flux is converted to a gaseous phase, while aggregates and non-combustible material remain as solid residue (bottom ash and tar). The generated hot flue gases from the combustion stage are recovered in a waste heat boiler where it generates steam. The superheated steam from the boiler can either be used for space heating or it can be pressurized and directed to rotate blades of a steam turbine which is coupled to a generator to produce electricity (Singh *et al.* 2001).

All combustible classes of waste such as plastic papers, plastic bags, plastic bottles, cardboards, wood, rubber, food waste, leather and clothing material can be incinerated. These wastes have different properties and elemental compositions and are abundantly available (Zeeshan *et al.,* 2021). Most advantageous is the fact that these materials have the potential to produce various types of value-added products in terms of energy and chemicals through the gasification process (Zeeshan *et al.,* 2021). However, because they differ in their characteristics in terms of composition, moisture content and calorific values; the incinerators can perform better with waste satisfying the basic requirements applicable for use in the WtE generation plants (Fiorucci *et al.* 2003). The most popular wastes that are easily available and can be incinerated are plastic materials and paper. These wastes represent 30–40% of the total MSW globally (Santibañez-Aguilar *et al.* 2013). Plastics and papers occupy an enormous volume of space for ages since they are non-biodegradable (Passamonti *et al.* 2012). But the question is: do these types of wastes satisfy the requirements for energy generation in terms of sufficient quantities, optimum moisture content and calorific values? This study aims to answer this question by describing the characteristics of wastes generated in the North-West Province (NWP), South Africa; analysing the status of the required information to initiate WtE generation projects and determining the potential for WtE projects to improve energy access to informal settlement households.

1.2. Overview of MSW Policy and Regulation in South Africa

Waste management policies have been developed and stated in European Union (EU) to set recycling and recovering targets, while avoiding the landfilling of waste as a waste management option (Antonopoulos *et al.,* 2014). The Environmental Conservation Act (Act 73 of 1989) [2] as amended is a legislation that sets the tone for waste management in South Africa. It sought out the requirements for the management of waste and provided the first legal definition of waste. But it was largely focused on the permitting, control, and management of waste disposal sites. The intention being to reduce the environmental impacts associated with many poorly operated landfills, many of which were in fact dumpsites (controlled and uncontrolled). The Waste Management Policy in South Africa is informed by the Schedule 5, Part B of the Constitution of the Republic of South Africa Act of 1996 that mandate local governments to perform cleansing function (RSA Constitution Act 108, 1996). The National Environmental Management Act 107 of 2008 illustrates that municipalities are expected to deliver waste management services which include amongst other things, waste removal and disposal. The legislative requirement promotes waste minimization, reuse, recycling while waste disposal (landfilling) is considered as a last resort. In South Africa, the National Environmental Waste Management Act (NEMA) requires that all municipalities prepare an Integrated Waste Management Plan (IWMP) with the aim of ensuring that the municipality provides waste management services that are compliant with the National Environmental Waste Management Act of 2008 (NEMA, 2008). The National Environmental Management (NEM): Waste Act (Act 59 of 2008) (RSA, 2008) promulgated in 2008 created the motivation for a further regulation that followed between 2008 and 2017, including the NEM: Waste Amendment Act (Act 26 of 2014) (RSA 2014).

1.3. Bridging the energy gap: energy generation from MSW in the North-West province

In many countries across the world, the socio-economic challenges have proved to be at the centre of the proliferation of informal settlements. Since the end of the apartheid era, rural-urban migration and the global integration of the South African economy has resulted in significant changes in the distribution of the population and the location of industries (Geyer *et al.* 2012). According to the Brown-Luthango *et al.* (2015), informal settlements are not peculiar to South Africa, they are increasingly the norm in Africa and in many other developing countries where the need for urban housing for the poor cannot be matched with delivery of any kind of formal housing. According to Statistics South Africa census data of 2012, more than 80% of the country's population live in informal settlements. In South Africa, as in many developing countries, informal settlements persist despite the government's targeted provision of low-cost housing (Huchzermeyer 2014).

A common factor in many cities around the world is that urban inhabitants consume large quantities of material especially the densely populated areas. Simultaneously from these areas, a lot of solid waste is released which include MSWs, industrial wastes, hazardous wastes etc. Exacerbating the situation is that most municipal authorities in South Africa are not equipped with the necessary skills, knowledge, and resources to implement a more efficient system of managing the waste. Consequently, as these solid wastes are discarded for a longer period, they become breeding grounds of vectors of different diseases and produce foul smell and poisonous gases. The surface run-off from the wastes cause water pollution, in addition gases produced from wastes cause air pollution. Unplanned waste dumping places becoming health hazards not only in the informal settlements but also in other nearby places. Therefore, with the purpose of avoiding these environmental problems, suitable methodologies should be adopted to dispose the wastes scientifically (WtE or composting) or to recycle them or segregate organic and inorganic wastes and recyclable wastes.

According to Statistics South Africa (2021), the most recent study of the energy, gas and water supply industry, reports some understanding of the present status of power supply characterised by great dependency on coal associated with persistent loadshedding. The burning of coal for energy production in South Africa leaves large quantities of fly ash, usually stored in ash ponds or landfills. Leachate from the unlined ash ponds and landfills have a high concentration of heavy metals, which infiltrate into groundwater, which consequently pollutes aquifers for decades or centuries (Tombs and Whyte 2015). Despite the energy problems in South Africa, every family requires energy for three main tasks: cooking, heating, and lighting. Electricity is an ideal source as it can be used to perform all these three tasks (NERSA 2021). However, majority of poor households located in the informal areas have no access to the power grid and in most cases cannot afford other forms of energy. The Free Basic Electricity policy (Stats SA 2017), mandates municipalities to provide suitable off-grid energy sources such as paraffin, liquid petroleum gas, bio-ethanol gel (or fire gel), and coal as options. Of South Africa's 213 local and metropolitan municipalities, 49 indicated that they are servicing indigent households with at least one form of off-grid energy source (Stats SA 2017). In this regard, besides the conventional renewable energy sources such as solar, the motivation for sustainable energy production from municipal solid waste to ensure healthy lives, promote well-being for all and ecosystem health cannot be overemphasised.

The quantity of waste available will determine the sustainability and capacity of the WtE generation project and competing interests (other waste treatment projects e.g., composting). Sufficient quantities of the wastes translate to continuous feed into the incinerator without disruption of the WtE plant operations (Fiorucci *et al.* 2003). If there is insufficient supply of the correct type of waste for the WtE process, the plant will be forced to stop until another lot of waste is generated. This is costly in terms of time, production output and income. Under these circumstances, the generation of energy will be more expensive than the cost of the energy generated. Therefore, adequate quantities of waste are a requirement for sustainability of WtE generation, however, moisture content, calorific values, and efficiency of the WtE technology should also be considered.

Waste with high moisture content affects the efficiency of the incinerator thereby reducing the output of the energy generated (Cheng and Hu 2010). Under such circumstances the process will require extra energy to aid the removal of water from the waste before the energy generation process starts. For example, in China, because of the high volumes of food waste, the moisture content of the waste is high, (typically around 50% compared to 20–30% in the U.S.A and European countries) (Cheng *et al.* 2007). This results in most Chinese incineration plants depositing the original waste in the waste pit for five to seven days to remove some of the moisture before the waste is fed into the furnace to keep stable burning and combustion (Zhang *et al.* 2010). Information on the moisture content of the waste affects the calorific values of the waste, making the WtE process either costly and unsustainable or efficient and cheap.

Calorific values of the MSW varies depending on the source, moisture content of waste and period of the year (i.e., wet or dry season) (Bai and Sutanto 2002). Calorific value of waste indicates the amount of energy that can be extracted from the different types of waste. Waste can be highly combustible, but not suitable for WtE generation. An example is in Singapore where about 85% of the solid waste generated was combustible, but the moisture content was considerably higher (48.6%) for incineration (Bai and Sutanto 2002). WtE generation process requires calorific value that is $\geq 7,000$ kJ/kg on average over a year (Demirbas 2001; Zerbock 2003) and the moisture content that is $< 55\%$ (Cheng *et al.* 2007).

Information on calorific values will aid the planners to identify the type of waste that has the optimum calorific values for maximum WtE generation; otherwise, it becomes problematic to determine the potential of WtE generation and conducting required modern waste management systems. The production of electricity from MSW remains largely untapped in Africa (Ofori-Boateng *et al.* 2013); however recent studies have documented that MSW from African cities could equally be utilised to generate energy. Ibikunle *et al.* (2019) concluded that the 584 tons of combustible municipal solid waste in Ilorin with 21 MJ/kg heating value has the capacity to produce 3.2 GWh of energy potential, 41MWof electrical power and 27 MW of power to grid. To select a WtE technology that will suit sustainable environmental, social, and economic WtE project, it is important to understand the specifications, cost, efficiency, lifespan, classes of waste and impact of the WtE technologies. This is only possible if there is information on the variables that are required for WtE generation.

Therefore, the focus of this study is to describe the requisite information required for the initiation of WtE generation project(s) in the North-West province of South Africa and beyond using a quantitative research approach. Specifically, the paper seeks to (i) describe the characteristics of waste generated in the NWP (ii) analyse the status of the required information to initiate WtE generation projects and (iii) determine the sustainability of WtE projects for energy access. The study argues that WtE offers many social, economic, and environmental advantages. Ultimately, this study contributes to the literature focusing on resource recovery from unused waste, reduction of pollution caused by poor waste management while ensuring the provision of sustainable energy to poor informal households. The findings of this study highlight the sustainability of WtE generation while protecting the environment from the negative effects of improper waste management and disposal prevalent in most developing countries including South Africa.

2. Methods

2.1 Description of the study area

The study was conducted in the North-West Province (NWP) of South Africa. NWP lies in the northern part of South Africa on the Botswana border. The province has 4 districts and 19 local municipalities (Fig. 1). It is known as the Platinum Province for it is the most important for platinum mining in South Africa

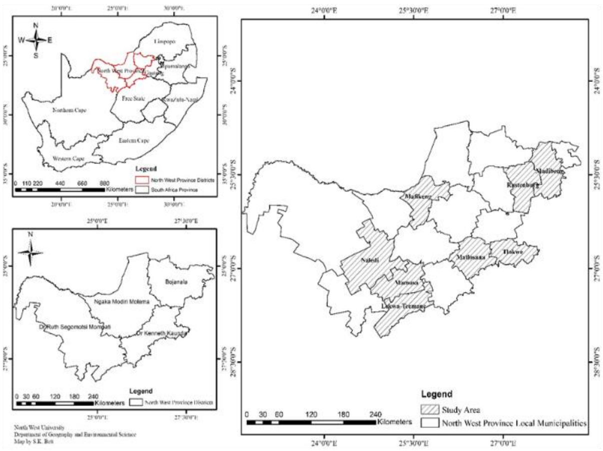

Fig. 1. North-West Province showing district and sampled municipalities

(Stats SA 2021). NWP covers a total area of 105, 076 km^2 which translate to 8.6% of South Africa's total area (Stats SA 2021).

2.2. Sampling

The population of interest in the study included the local municipalities targeting the individual waste directorate. The unit of analysis is the waste information system focusing on information that is relevant for WtE generation projects. A simple random sampling using a table of random digits was used to randomly select 8 local municipalities (Fig. 1). The local municipalities included in the study are depicted in Table 1. Assessment for each municipality focused on waste generation and volumes, existing treatment options, and landfill status. Each of the 8 local municipalities were visited for introductions and application for official permission to conduct the research. The visit was also used to identify and liaise with officials of the waste directorate who were asked to facilitate access to required secondary datasets. Thereafter, the waste directorates at each of the selected local municipalities were notified through formal letters of the date, time, and the duration of fieldwork. The study was approved by the North-West University (South Africa) Ethics Committee on Animal Care, Health, and Safety in Research (AREC-130913-015).

2.3. Data

Data was collected through secondary information from municipal, provincial, and national waste management directorates. This was done to identify the type of waste classes generated in the study area, volumes/quantities, population distribution, waste treatment options available as well as viability of the treatment options. The primary datasets were generated through fieldwork and consultations with officials for selected local and district municipalities in the NWP. For the field work, structured observation schedule was used to collect information on quantities, types, moisture content and calorific values of waste from landfills that were visited. The informal consultations were conducted with officials responsible for the individual waste directorates at local municipalities to validate information on the types of waste generated in the province, including volumes and waste treatment options (recycling, composting, and landfilling).

Table 1
Location of local municipalities

Municipal name	Location (Latitude and Longitude)	Municipal area (km^2)
Mafiikeng	-25° 54' 59" S, 25° 39' 59" E	3698
Naledi	-26° 49' 59" S, 24° 49' 59" E	6941
Mamusa	-27° 14' 60" S, 25° 14' 60" E	3615
Lekwa-Teemane	-27° 54' 53" S, 25° 09' 48" E	3681
Matlosana	-26° 52' 01" S, 26° 43' 10" E	3561
Tlokwe	-26° 43' 00" S, 27° 04' 59" E	6398
Rustenburg	-25° 18' 03" S, 27° 28' 04" E	3423
Madibeng	-25° 36' 12" S, 27° 49' 08" E	3839

2.4. Population and waste generation

2.4.1. Population estimates

The 2011 population census data formed the base to calculate the 2016 and 2020 population estimates for the municipalities and the province using Eq. 1:

$$Base\ year + n = X + (\frac{n}{1} * G_r * X) \quad (1)$$

where n = number of years to the next year(s), X = population for base year, $\boldsymbol{G_r}$= Population growth rate.

The 2011 population, growth rates and annual household income classes were extracted from the municipal profiles from Statistics South Africa (Stats SA 2012). Each municipality was profiled into four income categories in Rands (R), South African currency and for this study, the profiling was put into 3 categories: Low income: R0-R19, 200, Medium Income: R19, 201- R307, 200 and High Income: R307, 201 and above.

Using the percentages of population represented in each income level, total population estimates were calculated for each level for the selected municipalities using Eq. 2

$$P_L = \ L\% * \ P_y \quad (2)$$

where P_L= the population for low-income level; L% = Percentage of population represented in low-income level; P_y = Total population for the municipality each year (in this study it is the population for the years 2011, 2016 and the projected 2020). Equation 2 was also used for calculating population for medium income level (P_m) and population for high income level (P_H).

2.4.2. Waste generation volumes

Statistics about waste streams across South Africa and for individual municipalities only indicate estimates from industry sources with few field validation studies. This study computed the estimates of waste generation volumes using the available waste generation rates that were calculated for each income level by South Africa State of Environment Report (SOER) of 2006. The rates are as follows: low income 0.41 kg/person/day, middle income 0.74 kg/ person/ day and high income 1.29 kg/person/day.

For this report, Eq. 3 was used to estimate the 2011, 2016 and 2020 volumes of waste for the study area:

$$G_w = \ P_p * \ C_w * W\% \quad (3)$$

where G_w= General waste generated; P_p= Projected population; C_w= per capita waste generation and W% = % of waste per waste stream.

2.5. Experimental design

2.5.1. Moisture content

Moisture content was measured using a Fristaden TK-100G, VER. 15G30A Multifunctional Moisture equipment based on the electrical resistance probe technique. It is a high-tech testing instrument with extensive probes that suit many materials for moisture content testing (Gawande *et al.* 2003). The testing sequence started with waste collection from the landfills and separated into different classes of waste like plastics (bottles, papers), food, garden, textile, leather, wood, rubber, and papers (including cardboard). Each class of waste was put in a 5-litre plastic container one at a time. The moisture meter was switched on and set to zero then the probes were pressed into the sampled class of waste in the 5-litre container and readings were recorded for every class of waste. For precision purposes, the procedure was repeated 3 times for the same class of waste. The readings were recorded in Microsoft excel sheet and average moisture contents were calculated for each class of waste.

2.5.2. Calorific values of the waste

Determination of calorific value of each waste class was done using existing literature (Abu-Qudais and Abu-Qdais 2000; Visvanathan and Tränkler 2003; Sumathi et al. 2008; Kumar *et al.* 2009; Unnikrishnan and Singh 2010; Singh *et al.* 2001) and from existing and operational waste-to-energy plants to establish the optimum calorific values of each class of waste.

2.6. Statistical analysis

The collected primary and secondary data were tabulated and subjected to frequency computations using descriptive statistics. The outputs were presented in the form of applicable graphics to describe the situation as it existed at the time of the study.

3. Results and discussion

There are several factors that need to be considered when planning to recover energy from MSW through incineration. These factors include quantities, classes, composition, competing interests, moisture content, calorific values of waste and the waste processing technology options, so that optimal combinations can be selected and implemented (Kalyani and Pandey 2014). The potential of WtE generation in the NWP is discussed in relation to information on these factors.

3.1. Waste quantities in NWP

NWP shows an increase in population from 3,509, 953 in 2011 to 3, 539, 042 in 2016 including the projected population of 3, 562, 899 for 2020. Since there is no comprehensive information on the waste quantities and the classes of the waste in the province, the estimated population sizes, and the rates of generation of waste that were reported by the Department of Environmental Affairs (DEA) in 2012 were used in the estimation of the quantities and classes of the MSW for the NWP. The rates from DEA are used because DEA is the government mother body that takes care of all the information on waste in South Africa through South African Waste Information Centre (SAWIC) and SAWIS. The estimated quantities of waste generated in the NWP for were 7.7 x 10^3 tons/yr in 2011, 7.78 x 10^3 tons/yr in 2016 and projected to 7.84 x 10^3 tons/yr in 2020.

The increase in the MSW generation could be attributed to the rapid development that is observed in NWP from the main economic activities which are mining and farming. This has changed the lifestyle and fashion of the residents in the NWP. In addition, population growth and industrialisation which include the increase in employment contribute towards large-scale increase and change in the characteristics and composition of solid waste generated (Tan *et al.* 2014). The increase in waste quantities offers a potential that can sustain WtE projects to solve the energy problems that NWP informal households are facing.

Not all waste is suitable for energy generation, therefore, it is important to estimate the quantities of each class of the waste generated. This is vital because the classes of waste can be separated and allocated according to their use in different projects, for example, recycling, composting or WtE. The quantities of the classes of waste that were estimated for the NWP for the years 2011, 2016 and 2020 shows that there is high generation of papers followed by plastics with few rubbers. There are some waste classes whose quantities were not estimated but had marginal quantities, these included food, garden, textile, leather, and wood. The lack of data on these classes of waste could be due to no information on their generation rate in South Africa although they were observed at the landfills that were visited as part of the study. For this study, the volumes for garden waste and rubber were not calculated because these waste classes' follows composting and recycling respectively as final modes of waste treatment.

3.2. Competing interests

Waste is a resource that can be processed to generate a diversity of raw materials, semi-finished goods and final consumer goods for the market (Stehlik 2009). Critical to the determination of the sustainability of the quantities of waste for WtE generation, was the analysis of the different options of waste treatments that compete for similar waste class and quantities required. The competing waste treatments encompasses recycling, incineration, and composting (Fiorucci 2003).

In the study area, twelve waste treatment facilities were identified. There are only two types of waste treatments practiced in the study area namely: landfilling (91.7%) and recycling (8.3%). There is zero percent for both composting and

Table 2
Quantities of fractions of waste before and after removing waste for recycling

Fraction	Quantities (tonnes)					
	Recycled 2011	Remainder 2011	Recycled 2016	Remainder 2016	Recycle 2020	Remainder 2020
Plastics	4, 634	41, 708	4,675	42, 076	4, 708	42, 370
Textile	-	-	-	-	-	-
Leather	-	-	-	-	-	-
Wood	-	-	-	-	-	-
Rubber	772	6, 951	779	7, 013	785	7, 062
Paper	6, 179	55, 611	6, 234	56, 111	6, 277	56, 493

Source: Authors (2020)

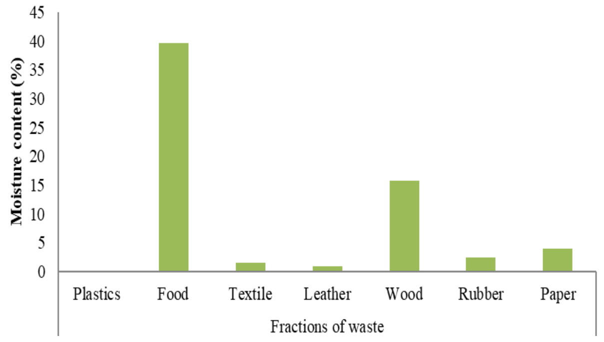

Fig. 2. Average moisture content of each fraction of waste in NWP

WtE generation. In this case, the study considered waste recycling as a competitor because it is the only waste treatment that has been recorded in the province. Table 2 shows the quantities of the different classes of waste that are used in recycling and the remaining quantities for the NWP; information which could be important in determining the feasibility of WtE projects. The results show that approximately 41, 000 tonnes/year of waste is available for alternative waste treatment besides recycling.

3.3. Moisture content of the MSW

One distinct characteristic of MSW in developing countries is its high moisture content level (typically around 50%), which is much higher than that of developed countries, like the United States of America (20-30%) (Cheng *et al.* 2007). Waste with high moisture content is not ideal for WtE generation. However, in NWP the landfills have no sections for waste segregation for the waste classes. Local municipalities still follow the pipe-approach in forwarding mixed waste to landfills. The waste goes to the landfill and the waste pickers do most of the sorting. This means that at landfills, waste is exposed to climatic conditions such as rainfall and variations in temperature. At the landfills, there is no moisture content information collected. Consequently, for this study, the moisture content of mixed waste and each of the classes of waste had to be measured. The exercise was done at landfills that are in 3 different rainfall regions of the NWP classified as low (average rainfall of ±250mm), medium (average rainfall of ±450mm) and high (average rainfall of ±600mm).

The results depict that rainfall affect the moisture content of waste whereby the high rainfall regions, the moisture content is above 10% compared to low rainfall regions (about 5%). The overall moisture content of each class of waste are listed in Fig. 2. Five of the waste classes have less than 10% of moisture content, the lowest being 0.2% and the other three having over 14% with the highest being that of food waste class (39.6%). The optimum moisture content for waste to be used for WtE generation is approximately < 55% as supported by Cheng *et al.* (2007) and Iakovou *et al.* (2010). Cheng *et al.* (2007) pointed out that incinerators could adapt to MSW with a wide range of moisture contents of up to 55% because the technology can remove the moisture content without using much of extra fuel.

As noted by Iakovou *et al.* (2010), it is possible to burn any type of biomass but in practice, combustion is feasible only for biomass with inherent moisture content of less than 50%, above which pre-drying is feasible. The waste generated in the NW province is eligible to be used in incinerators for WtE generation as its moisture content range from 0.2- 39.6%. The moisture content is lower than the optimum average moisture content that is required for WtE generation process. The low moisture content of waste in the study area could be attributed to the small quantities of food waste in the landfills and that most of the food waste was almost dry at the time of data collection. Cointreau (2006) stated that where there is less food waste and other organic waste, the moisture content is low, for instance in high income countries.

Climatic differences also play an important part on the moisture content of waste, for example comparing the situations of the moisture contents of the waste in the study area (which is low) to Singapore's (which is high); it is noted that Singapore has average temperature of 24.7-31.3 °C, daily average humidity at 84.4%, and annual average rainfall of 2134 mm (Bai and Sutanto 2002) while NWP of South Africa is a dry area and has higher average temperatures (22~34 °C) and overall annual average rainfall (432mm) (Walker and Schulze, 2008). In addition, evapotranspiration rate is the key factor to the moisture content of the waste in these different rainfall regions. Evapotranspiration is related to temperature, wind, humidity, atmospheric pressure, soil moisture content, and solar radiation (Al-Yaqout and Hamoda 2003). If the region has high rainfall and lower temperatures, evapotranspiration rate is low, consequently the waste that is dumped in such areas take long to release the water, hence high moisture contents (Gawande 2003). Also, Belsky *et al.* (1993) in a study on high and low-rainfall savannahs in Kenya, linked the high moisture content to high rainfall. In Indian cities of Shillong, Kohima, Simla and Agartala a higher moisture content in the MSW was observed (65 %) due to heavy rains (Kumar *et al.* 2009). In the regions that have low rainfall and high temperatures, the evapotranspiration rate is high causing the waste that is dumped in these areas to release the water rapidly, hence low moisture content. For the NWP, information about the rainfall region and subsequent moisture content will advise on the source of collection of waste to be used in WtE plants during different seasons of the year. Although the range of moisture content of the waste in NWP shows that it is ideal for WtE generation projects, it is still a challenge to estimate the potential for WtE generation without the information on calorific values.

Table 3
Calorific values of waste from other countries

Calorific value (kJ/kg)	Region	Author(s)
11,500	Jordan	Abu-Qudais & Abu-Qudais (2000)
2,000-4,000	Asia: India, Sri Lanka and China	Visvanathan & Trankler (2003)
1,900-2,600	Pondicherry, India	Sumathi *et al.* (2008)
2,000-15,500	India	Kumar *et al.* (2009)
3,400-4,500	China, India, Brazil and Argentina	Unnikrishnan and Singh (2010)

Table 4
WtE technologies and energy generation

Capacity of incineration technology (tonnes/day)	Moisture content of waste (%)	Calorific value of waste (kJ/kg)	Energy generated (GWh)	Author
600	< 55	9630	0.247	Otoma *et al.* 1997
960	< 55	9000	0.726	Rand *et al.* 2000
240	< 55	10400	29.500	Zsigraiova *et al.* 2009
24000	< 55	8800	14.940	Tsai & Kuo 2010
700	≥ 55	9204.8	0.192	Kadir *et al.* 2013
154,000	45-65	3000- 5000	62.400	Zheng *et al.* 2014

3.4. Calorific value of MSW

The basic assumption for utilising MSW as fuel in an incinerator for WtE generation is its sufficient heating value (Tabasová *et al.* 2012). Therefore, this study considered the calorific values of MSW in NWP. Calorific value is the energy content of the waste which indicates the amount of energy that can be extracted from the waste for energy generation (Rand *et al.* 2000). The optimum calorific values of waste that are appropriate for WtE generation should exceed 7,000kJ/kg, otherwise any value below this, the WtE generation technology will need external fuel to remove the water first from the waste (Demirbas 2001).

The calorific values of mixed MSW for the selected regions range from 1,900- 15,500kJ/kg. However, due to lack of information on the calorific values of waste for NWP, this study used data from literature. The choice of literature was governed by geographical regions. Table 3 lists the calorific values of waste from regions that lie in the same climatic region as South Africa and those that have climatic similarities to NWP (semi-arid environments). The countries with similarities to South Africa include México, Argentina, and Australia but it is also the same with some countries in Asia like India, China, Sri Lanka, and Thailand.

The calorific values of mixed MSW for the selected regions range from 1,900- 15,500 kJ/kg. The wide range could be because the wastes were not separated at source (Narayana 2009). However, Abu-Qudais and Abu-Qdais (2000), Iakovou *et al.* (2010) and Narayana (2009) attributed the low calorific values to high moisture content and organic contents of some of the waste. There is also information for calorific values for each class of waste that was compiled by Rand *et al.* (2000) from literature for the subtropical region with the same geographical and climatic similarities as South Africa (Table 3).

Analysis of calorific values of waste generated in South Africa for some of the individual classes of the waste shows higher calorific values than the expected minimum value of 7,000 kJ/kg (Rand *et al.* 2000). Specifically, plastics have the highest calorific value (20,144 kJ/kg), and the lowest is food waste with calorific value of 1,912 kJ/kg (Rand *et al.* 2000). Other classes of waste such as wood, textiles as well as leather and rubber have the optimum calorific values of 9,310 kJ/kg, 14,265 kJ/kg and 11,789 kJ/kg respectively with potential of WtE generation. Demirbas (2002) and Zerbock (2003) suggested that for incineration, the minimal heating value must on average be at least 7,000 kJ/kg because the low heating value of MSW will affect the economics of incineration especially for power generation.

The study further shows that there is need to have information on the income levels of the areas where the waste is collected. The income level has an impact on the volumes and class of waste generated and consequently the moisture content and calorific values. According to Cointreau (2006), the moisture content and calorific values of low-income countries ranges between 40-80% and 3,000-4,000 kJ/kg respectively. For the middle-income countries, the moisture content range between 40-60% and calorific values have the heating potential of 4,000 and 6,000 kJ/kg. High income countries depict lower moisture content in the range of 20-35% with high calorific values of 6,000-11,000 kJ/kg.

Waste generated in the NWP shows that the highest moisture content is 39.6% which is slightly above the 35% for high income countries and slightly below the 40%. The calorific values range between 1,912-20,144 kJ/kg. This can be explained by the fact that NWP is in South Africa and the country is categorised as an upper middle-income country and therefore characteristics of its waste could be identical to the waste in the middle-income countries. Calorific values are affected by the moisture content; the higher the moisture content the lower the calorific value (Komilis *et al.* 2009). Pearson's correlation analysis was run to assess the effect of moisture content on calorific values. The results of the Pearson's correlation analysis revealed that there is a significant relationship between moisture content and calorific value (R^2=0.036; p≤0.05). However, the relationship is negative (R^2= -0.739), indicating that the higher the moisture content of the waste, the lower the calorific value.

3.5. Waste processing technologies

Several studies have been conducted on the use of MSW for energy production and some even provide estimates of the energy potential of the waste. To select a WtE technology that will suit the environmental, social, and economic situation, it is important to understand the specifications and impact on the environment. This is only possible if there is information on the waste (quantities and characteristics) and the technologies to be used. Different sizes of WtE generation technologies have been adopted for energy generation in WtE plants worldwide. The size and amount of energy that is generated is determined by the capacity of the incineration technology. Capacity of the incineration technology indicates the quantity of waste (in tonnes) that is fed into the technology per day. Table 4 shows different sizes of WtE generation technologies, conditions that affect the energy generation and the estimated energy that they generate per day.

Apart from moisture content and calorific values, energy generation also depends on the capacity of the technology. Assuming all conditions are optimal, the higher the capacity of the incineration technology, the more the energy that is generated. With unclassified MSW, 75,000 tonnes will generate approximately 15,000 MWh of electricity considering the calorific values of >3300 kJ/kg and moisture content of <55% (Cheng *et al.* 2007). In this case, each ton of MSW could generate approximately 200 kWh electricity (Cheng and Hu 2010).

For situations like the NWP where the generation of waste is less than 50,000 tonnes/year (~137 tonnes/day), there is a need to identify appropriate technologies with ideal capacities. Therefore, this study adopted the technology capacity of 240 tonnes/day proposed by Zsigraiova *et al.* (2009). Technologies

Table 5
Summary of moisture content, calorific values, and quantities per year of fractions of waste

Fraction	Moisture content (%)	Calorific value (kJ/kg)	Quantities (tonnes)		
			2011 NWP	2016 NWP	2020 NWP
Plastics	0.2	20, 144	46, 343	46, 751	47, 078
Food	39.6	1, 912	-	-	-
Garden	14.9	1, 912	-	-	-
Textile	1.5	11, 789	-	-	-
Leather	1.0	14, 265	-	-	-
Wood	15.8	9, 310	-	-	-
Rubber	2.4	14, 265	7, 724	7, 792	7, 846
Paper	4.0	6, 440	61,790	62, 335	62, 770

Source: Authors (2020)

with this capacity can be used as stand-alone WtE generators in households, farms, and factories.

3.6 Waste-to-energy generation in the NWP

Implementation of WtE generation projects can only be feasible when all the variables discussed above, are ideal and known. Any combustible waste can be used in incinerators but only those with the optimum moisture content, calorific values and adequate quantities would be suitable in efficient WtE generation process. The assessment done so far indicates that the moisture content for all classes of waste generated in the NWP is ideal and for calorific values, 83.3% of the classes are appropriate for WtE generation. The eligibility of the wastes to be used in WtE generation projects is dependent on the quantities generated. Table 5 is a summary of the average moisture content, calorific values, and quantities of classes of the waste for 2011, 2016 and the 2020 projections for NWP.

The summary in Table 5 reveals that although there is missing information on quantities of some of the classes of the waste for 2011, 2016 and 2020, the moisture contents that are known for some of the classes of waste are in the proper and ideal ranges for WtE generation, (<55%) which is regarded as the recommended moisture content for WtE generation. It also depicts that some of the classes of waste have the optimum calorific values for WtE, which is more than the minimum recommended value of 7,000kJ/kg. These are plastics, textile, leather, wood, and rubber constituting 62.5% of the waste classes. However, of the 62.5% classes of waste, only plastics and rubber have information on quantities. Therefore, the estimation of WtE generation was based on these two classes of waste.

Based on the estimated quantities of individual waste classes for the NWP, calculations were done to determine the number of days of operation for the selected WtE generation technology. Furthermore, energy generation from the 3 classes of waste was also estimated for the NWP. The energy calculations were based on Zsigraiova *et al.* (2009) assumptions that a WtE technology of 240 tonnes/day, moisture content of <55 %, and calorific value of 10000 kJ/kg generates 29.5 GWh. The results summarised in Table 6 shows the number of days and the different quantities of waste classes if used in the 240 tonnes/day WtE generators. Besides, the results depict the estimated energy that would be generated from each of the 3 classes of wast Using paper as fuel in the 240 tonnes/day WtE technology would cover more days of operation than the other two waste classes. Based on the 2016 and 2020 estimated waste quantities, paper would last 234 days and generating about 6, 897 GWh and 235 days with 6, 944 GWh of operation respectively. On the other hand, for plastics, WtE generation would cover only 175 days for 2016 data generating 5, 171 GWh and 177 days for 2020 data with energy output of 5, 207 GWh. The results also show that if rubber is used as fuel in this technology, it would cover just a month of operation (29 days both for 2016 and 2020 data). However, if the waste classes were mixed, the total quantities can sustain operation of the WtE technology for over 365 days (1 year).

4. Conclusion and recommendations

The results of this study revealed information on all the variables that affect the process of energy recovery from MSW which includes quantities, classes, moisture content, calorific values of waste and the technologies used. This information is decisive in determining the sustainability of WtE projects in relation to other waste treatment projects, selection of the correct waste treatment for waste and selection of the correct technology for waste treatment. The results also show that in terms of calorific values and moisture contents, most of the waste classes are suitable for WtE generation. The only obstacle to the projects is the inadequate quantities of the individual classes of waste generated in the province which cannot sustain WtE generation for a year. However, combining the quantities of different classes could amount to the recommended quantity for annual generation of energy through incineration. Besides, WtE technology affords South Africa a solution to the current waste management problems which not only alleviates the

Table 6
Potential of energy generation in NWP

Capacity of a technology (tonnes/day)	Class of waste	Estimated quantities 2016 (tonnes)	Projected quantity 2020 (tonnes)	Estimated period (days)		Estimated energy generation (GWh)	
				2016	2020	2016	2020
240	Plastics	42, 076	42, 370	175	177	5, 171	5, 207
240	Rubber	7, 013	7, 062	29	29	861	867
240	Paper	56, 111	56, 493	234	235	6, 897	6, 944
Total		**105, 199**	**105, 925**	**438**	**441**	**12, 930**	**13, 018**

amount of waste being landfilled but also produce energy for off-grid informal residents. Thus, achieving Sustainable Development Goal Number 7 to ensure access to affordable, reliable, sustainable, and modern energy for all as well as waste management.

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