Techno-economic Assessment of Decentralised Waste Beneficiation in South Africa

by

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Supervisor Acknowledgement

As the candidate’s supervisor, I agree to the submission of this dissertation.

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Date: 12/08/2022

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ABSTRACT

The introduction of the waste hierarchy promotes the diversion of waste away from landfills towards value-adding opportunities. However, there is no clear methodology for the comparison of waste beneficiation pathways for decentralised waste treatment options in South Africa. As a result, most waste is landfilled in the country even though it contains large amounts of recyclable and recoverable materials. This study investigates the use of techno-economic assessments to determine the viability of decentralised waste treatment options and compare them to larger scales in three selected South African locations (Calvinia, Garden Route District, and eThekwini). These preliminary results may estimate economics before intense, expensive, and time-consuming design and scoping are performed.

A critical investigation of currently available literature from various data sources is performed to determine the national and local municipal waste landscape. This scoping exercise is essential for determining the variations of waste volumes and composition dependent on municipality size, which affect the capacity of the various treatment options. Hence, feedstock quantities are established for use in the techno-economic assessment. The three technologies assessed are engineered composting, anaerobic digestion, and pyrolysis of plastics, as examples of technologies that can be applied in various municipalities. Based on a simple cost-benefit analysis, techno-economic parameters are used to investigate the project feasibility based on historical Capital Expenditure data and certain assumptions for Operational Expenditure.

Furthermore, a Discounted Cash Flow analysis assesses the variables of Net Present Value (NPV), Pay Back Period, and Internal Rate of Return. These assessments are considered preliminary, with an accuracy ranging between 30% and 50%. Sensitivity analysis determines the different breakeven points of the different economic parameters, indicating feasibility in the event of market fluctuations.

Six different scenarios are investigated: the separation and recycling of waste streams (scenario 1), engineered composting (scenario 2a), anaerobic digestion (scenario 2b), pyrolysis of plastics (scenario 2c), and combination scenarios (composting and pyrolysis (scenario 4a), as well as anaerobic digestion and pyrolysis (scenario 4b)). The separation and recycling of waste from each location found a credit of R2.4 to R17.8 / t waste based on specific assumptions. The increase in municipality size positively influences the feasibility of this scenario. The economic parameter of the Net Present Value is used to analyse the feasibility of the remaining scenarios. None of the scenarios is economically feasible in Calvinia, with Net Present Values less than zero. Composting is feasible in the Garden Route District and eThekwini with a Net Present Value of R44 million and 89 million, respectively. Based on electricity sales, anaerobic digestion is feasible in Garden Route District (R14.5 million) and eThekwini (R208.6 million). Plastic waste pyrolysis is feasible in the Garden Route District and eThekwini. The combined pyrolysis scenario with either composting or anaerobic digestion also produces feasibility in

the Garden Route District and eThekwini, with higher Net Present Values for the latter scenario. The inclusion of Extended Producer Responsibility targets decreases the Net Present Value of pyrolysis by reducing the amount of product and thus the revenue from fuel. Suppose Extended Producer Responsibility targets were fulfilled, and the recyclate stream was diverted to the Buy Back Centres for sales, the overall income could not overcome the capital and operational costs in any location.

The different parameters investigated through sensitivity analysis determine the leverage points for each process and inform the influence of market fluctuations due to legislative instruments such as the Extended Producer Responsibility. The landfill credit can be considered a key parameter since the true cost of landfilling is not widely recognised and may be underestimated. This is exhibited by the minimum landfill cost of R577, R711 and R365/ t waste for the feasibility of the separation and recycling scenario.

Separation and recycling is the only economically viable scenario in Calvinia, indicating that decentralised separation and recycling of waste is possible and should be considered in these locations. However, scenarios with higher capital and operational costs (scenarios 2(a)-(c) and 3) are not feasible. In such cases, incentives and government funding schemes must be investigated to support waste treatment opportunities in decentralised locations. As scale increases, all investigated scenarios became feasible in Garden Route District Municipality and eThekwini, indicating that the possible combinations of waste from different decentralised locations (i.e. multiple smaller municipalities like in the Garden Route District Municipality) could result in feasible treatment options in these parts of the country.

Furthermore, between 35 and 72% of landfilled waste can be diverted through the different scenarios (depending on Extended Producer Responsibility targets and local compositions), indicating that such process implementation can aid South Africa in reaching diversion targets set in the National Waste Management Strategy and Polokwane Declaration.

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List of Abbreviations, Units and Measures

Acronym	Definition
%	per cent
a	annum
AD	Anaerobic Digestion
ADT	Articulated Dump Truck
APWC	Asia Pacific Waste Consultants
BBC	Buy Back Centre
C	Carbon
CAPEX	CAPital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
CDM	Clean Development Mechanism
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon Dioxide
CSIR	
DAT	Dome Aeration Technology
DCF	Discounted Cash Flow
DEA	Department of Environmental Affairs
DEFF	Department of Environment, Forestry and Fisheries
DST	Department of Science and Technology
DSW	Durban Solid Waste
EA	Enumerated Area
EAP	Environmental Assessment Practitioner
EC	Eastern Cape
EIA	Environmental Impact Assessment
EPR	Extended Producer Responsibility
FCI	Fixed Capital Investment
FPC	Fixed Production Costs
FS	Free State
GHG	Greenhouse Gases
GP	Gauteng
GRDM	Garden Route District Municipality
H	Hydrogen

HDPE	High-density polyethylene
HHHW	Household Hazardous Waste
HVF	hot ceramic vapour filter
IEA	Internation Energy Agency
IPP	Independent Power Producer
IRR	Internal Rate of Return
IWMP	Integrated Waste Management Plan
KZN	KwaZulu Natal
LDPE	Low Density Polyethylene
LP	Limpopo
LHVdry	Lower heating Value
MARR	Minimum Acceptable Rate of Return
MBT	Mechanical Biological Treatment
MFMA	Municipal Finance Management Act
MP	Mpumalanga
MSA	Municipal System Act
MSW	Municipal Solid Waste
n	Scaling factor
NC	Northern Cape
NDP	National Development Plan
NEM: AQA	National Environmental Management: Air Quality Act
NEM: WA	National Environmental Management: Waste Act
NEMA	National Environmental Management Act
NNCRP	National Climate Change Response Policy
NOx	Nitrogen Oxides
NNCRP	National Climate Change Response Policy
NPV	Net Present Value
NRF	National Research Foundation
NW	North West
NWA	National Water Act
NWMS	National Waste Management Strategy
O	Oxygen
OPEX	Operational expenditure
OOM-TEA	order-of-magnitude techno-economic assessment
PE	Polyethylene

PET	Polyethylene Terephalate
PBP	Pay Back Period
PP	Polypropylene
PROs	Producer Responsibility Organisation
PS	Polystyrene
PVC	Polyvinyl Chloride
r	Discount rate
RMC	Raw Material Costs
ROR	Rate of Return
SA	South Africa
SAWIC	South African Waste Information Centre
SoWR	State of Waste Report
SOx	Sulphur Dioxide
SP	Selling Price
StatsSA	Statistics South Africa
TCI	Total Capital Investment
TEA	Techno Economic Assessment
TPC	Total Production Costs
TRL	Technical Readiness Level
TWC	Total Working Capital
UK	United Kingdom
UNEP	United Nations Environment Programme
USA	United States
USD	US Dollar
VPC	Variable Production Costs
WC	Working Capital
WC	Western Cape
WCI	Working Capital Investment
WHO	World Health Organisation
WTE	Waste to Energy
ZAR	South African Rand

Unit	**Measure**
°C	Degree Celsius
GW	Gigawatt
J	Joule
kCal	Kilocalorie
kg	Kilogram
Kg/day	Kilograms Per Day
Kg/hh/day	Kilogram Per Household Per Day
Kg/pp/day	Kilograms Per Person Per Day
kJ	Kilojoule
km	Kilometre
kV	Kilovolt
kW	Kilowatt
kWe	Kilowatt Electrical
kWh	Kilowatt-Hour
kwh	Kilowatt-Hour
m^3	Cubic Meter
MJ	Megajoules
Mt	Million tons
MW	Megawatt
R	Rands
R/t	Rand per ton
t	ton
tpd	Tons per day
tpm	Tons per month

CHAPTER 1: INTRODUCTION

Waste has become a major concern globally; with initiatives to form a more circular environment, the need to invest in waste treatment and recovery practices is imperative to move away from the "take, make, waste" society. There is little regard for waste as a secondary resource, with an overall dominance of landfilling in South Africa (Godfrey, 2019; Nahman, 2021). Literature suggests that waste services are disproportionate throughout the country. The level of service provided by various municipalities differs significantly: typically, large municipalities provide complete waste collection and disposal services, while smaller municipalities, usually found in rural communities, receive little to no services (Friedrich and Trois, 2011; Rodseth et al., 2020; DEFF, 2020a). Furthermore, alternative waste treatment options are generally considered expensive and stream specific, requiring separation of materials (not traditionally practised in South Africa) (Nahman, 2021). However, there are multiple long-term benefits of diverting waste to alternative treatments, such as cost-saving associated with the extension of landfill lifespan and environmental benefits (Nahman, 2021).

Although research is conducted on waste beneficiation, no clear methodology has been established, especially for decentralised areas. Economic feasibility is a major enabling factor in promoting the uptake of alternative solutions. However, the relative lack of diversified treatment practices means a deficiency of baseline data to inform decisions in the waste sector. A cost-benefit analysis is essential for investors and can promote ventures into the waste sector. Therefore, the economic feasibility of secondary waste products must be considered to incentivise waste treatment options in the country and direct research into possible value streams that have been excluded in the past. This study focuses on the techno-economic feasibility of different waste treatment options for Municipal Solid Waste (MSW) in decentralised locations and compares to larger sized municipalities in South Africa. The techno-economic assessment uses an order of magnitude approach to provide preliminary feasibility data to inform waste management decisions based on historical data. Additionally, it can inform current waste data and decision making tools in the evolving waste sector.

According to location-specific data, the assessment uses literature data to determine the Capital Expenditure based on the available waste. After that, the Operational Expenditure is determined using assumptions. Finally, a Discounted Cash Flow analysis is performed to determine key economic parameters to compare the different options and display the effects of waste disparity in the country. According to Naidoo (2020), the Technical Readiness Level (TRL) is used as an evaluation criterion to account for the technical maturity of technologies. The TRL of 1-4 can satisfy the order of magnitude approach used in techno-economic assessment, whilst more detailed data is required as the project develops. However, TRLs 7-9 offer more accurate results using the order of magnitude approach.

Although the waste hierarchy is promoted in South Africa, the low cost of landfilling waste means there is little incentive to look into waste treatment options higher on the hierarchy resulting in municipalities not considering alternative options (Nahman, 2021). According to Nahman (2021), there is much emphasis on economic instruments to incentivise waste movement up the waste hierarchy in South Africa for diverting waste from landfills towards alternatives such as recycling. Therefore, a techno-economic assessment is expected to be of national importance as a key decision-making tool in the waste sector. An example is the Waste to Energy Roadmap, a project between the South African Research Chairs Initiative and the South African National Energy Development Institute (IEA Bioenergy, 2022). Furthermore, the methodological approach and results of this study can provide the relevant techno-economic analysis optimisations and provide an indication for localised solutions through selected location scenarios, which also fall within the goals of the roadmap.

Knowledge gaps are noted due to the lack of sufficient and updated baseline waste profiles in South Africa at a municipal and national level. This study relies on available data, which in many cases was insufficient and required assumptions. Furthermore, due to the generally low costs of landfilling, country specific capital and operational costs for different waste treatment options are lacking within the country. Again, this was overcome by defining certain assumptions when undertaking the techno-economic assessment.

1.1. Problem Statement and Aim

According to field analysis of waste consultants who visit decentralised areas (such as Calvinia), many waste management challenges are encountered and are repetitive in many towns in the country (Nell and Schenck, 2018). Commonly, plastic is the main constituent of litter on the streets. There are only a few entrepreneurs that collect waste for recycling but are constrained by the location of recyclers some hundred kilometres away. The high operational costs involved, mainly due to the vast distances of transport required and the absence of working rail infrastructure, result in not feasible options in such locations (Nell and Schenck, 2020). Waste management usually competes for funding with other municipal departments such as housing, electrification, and water provision, often not receiving the required attention. In general, landfills in rural areas are not well managed, if managed at all (Nell and Schenck, 2020). This has led to the investigation of localised/decentralised solutions to waste management challenges, with the aim to determine which waste treatment option would be economically viable, taking local conditions into consideration.

Drivers towards sustainable waste solutions include:

- Divert waste from landfills and promote waste diversion targets set by waste legislative frameworks
- Provide secondary waste products, promote a competitive market for such products, and provide cleaner energy and fuel sources
- Decrease environmental degradation and pollution and aid in climate change mitigation
- Promote social aspects such as job creation and betterment of rural communities
- Create investment opportunities and provide preliminary feasibility methodology and results for the uptake of alternative waste technologies in the country

1.2. Objectives of the Dissertation

The objectives of this dissertation are summarised as follows:

- Conduct a desktop study on the current waste statistics in South Africa, determining what wastes are available (source, volumes, composition, frequency, etc.) in rural/urban municipalities, what is currently being done with these wastes in management/ disposal, what technologies can be used to upcycle wastes (description, economic data from historical plants) and which ones are applicable;
- Conduct a desktop study using an order of magnitude approach techno-economic assessment to determine the viability of waste treatment processes from household waste; and
- Conduct a simple impact assessment based on different criteria for each waste treatment option

1.3. Research Questions

The following research questions emanate from the objectives:

1. What are the waste types available in rural and urban areas?
2. What technologies are available to divert waste away from landfills within these locations?
3. How does techno-economics affect the uptake of waste treatment options in rural areas, and how would scaling up to urban areas affect feasibility?
4. How does scaling, i.e. amount and type of waste, affect the feasibility?
5. How do legislative changes such as the Extended Producer Responsibility (EPR) affect the feasibility of waste treatment?

1.4. Scope of study

The scope of this study to meet the objectives and answer the research questions above includes:

- Reviewing various data sources to determine the South African service delivery and waste landscape to determine the necessity, if any, for different waste treatment options.
- Selecting and investigating three municipalities, different in size and thus type and quantity of waste, by gathering data on waste fractions and existing disposal methods from literature. This allows for the identification of feedstock volumes for the techno-economic assessment.
- Critically reviewing the respective legislation to determine how current legislation in South Africa affects the uptake of different technologies, focusing mainly on the EPR.
- Assessing three technologies identified above, namely engineered composting, anaerobic digestion and pyrolysis of plastics, as examples of technologies that can be applied to the various municipalities.
- Identifying techno-economic parameters based on a simple cost-benefit analysis to investigate the project feasibility based on historical CAPEX data and assumptions for OPEX. Further, using a discounted cash flow analysis to assess the variables of Net Present Value (NPV), Pay Back Period (PBP) and Internal Rate of Return (IRR). These assessments are considered preliminary, with an accuracy ranging between 30% and 50%.
- Thereafter, conducting a sensitivity analysis to determine the different breakeven points for different economic parameters. This allows an indication of feasibility in the event of market fluctuations.

1.5. Structure of this Dissertation

This dissertation is sectioned into five chapters. A brief introduction highlighting the waste dilemma and problem statement for the study is introduced in **Chapter 1**. **Chapter 2** provides a literature study of the waste patterns, positions, and disposal methods at a South African country level. The legislative landscape of this study is presented. The chapter further outlines the investigated municipalities, treatment options and techno-economic calculations. **Chapter 3** provides a detailed methodology for the study describing the techno-economic assessment, economic analysis, and impact assessment for individual and combined scenarios. The results and discussion are found in **Chapter 4,** sectioned into techno-economic results and impact assessment for the different scenarios. The conclusions derived from this study are presented in **Chapter 5,** with recommendations for future work in **Chapter 6**.

CHAPTER 2: LITERATURE REVIEW

Chapter 2 overviews the literature on waste compositions, quantities, and current practices, in urban and rural areas. The legislative policies concerning waste in South Africa and the possible treatment options are briefly explained. Finally, an introduction to techno-economic assessment is described.

2.1.The South African Waste Context

According to World Bank definitions, South Africa has a high level of income polarisation with a dominance of low-income earners, decreasing as income increases (World Bank, 2018). The South African Constitution states the right to basic services, with the government aiming for equality. However, disparities still prevail in the different provinces of the country.

A visual representation of the national population settlement dynamics in South Africa, using the CSIR's updated Functional Town Topology, is presented in Figure 2-1(Van Huyssteen et al., 2018). This land topology shows that rural settlements are scattered over the country, with concentrations in its eastern and southern parts. Four major city areas are found: Gauteng, Cape Town, eThekwini and Nelson Mandela Bay City Region Areas, represented by large brown markers. As seen by the smaller green markers in Figure 2-1, rural nodes (including service towns and rural settlements) are found in clustered and dispersed settlements throughout the country (Van Huyssteen et al., 2018). The CSIR also projected that by 2030, about half of the population would live in urban areas.

The number of households that are considered "poor" is visually represented in Figure *2-2* (CSIR (StepSA), 2015). In 2011, about 1.2 million households lived in poverty (Mans, et al., 2015). According to the colour legend in Figure 2-2, blue and green show households less than 100, yellow indicate 101 to 500 households, and orange and red indicate up to 15 000 households living in poverty per an identified mesozone. High concentrations of poverty are found in or close to the four major city areas identified in Figure 2-2. In accordance with the population dynamics, high poverty levels are noticed in the Eastern Cape and KwaZulu Natal, with rural populations of over 50%. Furthermore, social classes show a correlating split in South Africa, with a concentration of poverty households in previously disadvantaged areas, namely KwaZulu-Natal, Eastern Cape, and Limpopo (World Bank, 2018; Stats SA, 2011).

A study of the post-apartheid landscape in the country found that a significant number of the underclass are poor and without land. Usually, the underclass migrates to more urban areas for jobs and social benefits from the government (Toit, 2017). StatsSA (2019) found that about 40% of all households do not have any income source, with social grants being the primary income source for 20% of households. The economy of these settlements is usually based on remittances, grants, and subsidies (DEFF, 2020a). In most instances, waste is closely correlated to income level, as higher income groups produce more waste attributed to the ability to purchase more packaged goods.

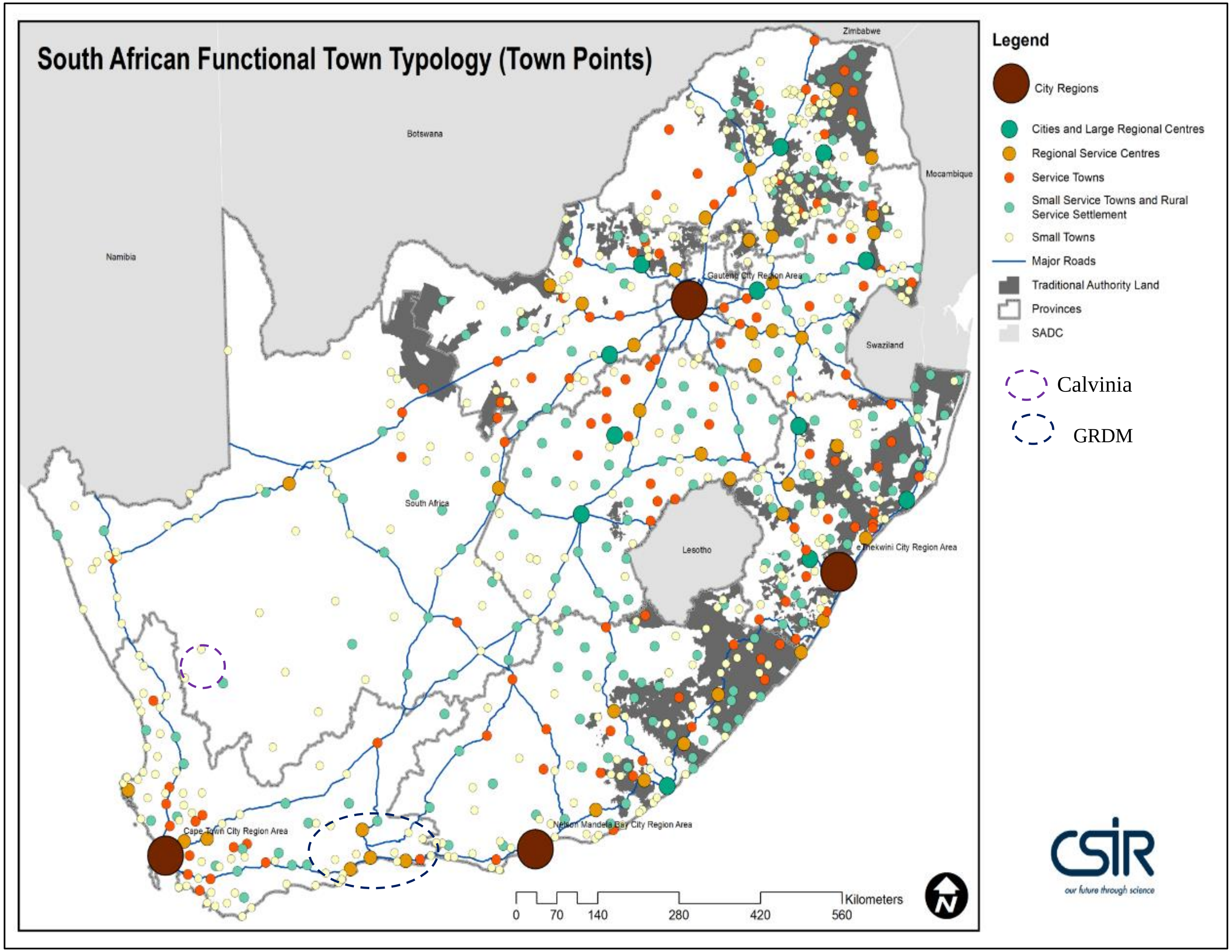


Figure 2-1: The South African town regional anatomy updated by CSIR in 2018 (Van Huyssteen et al., 2018)

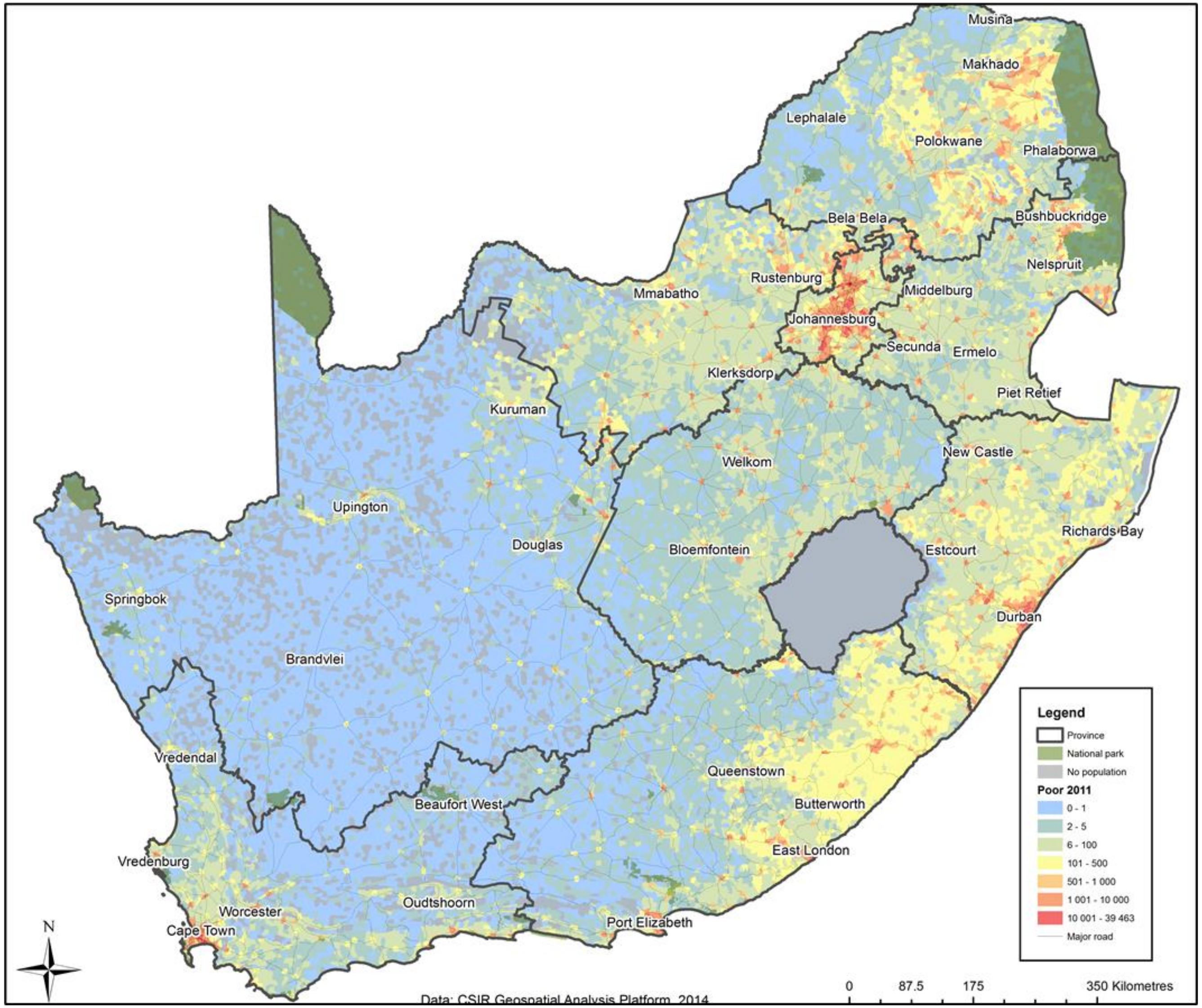


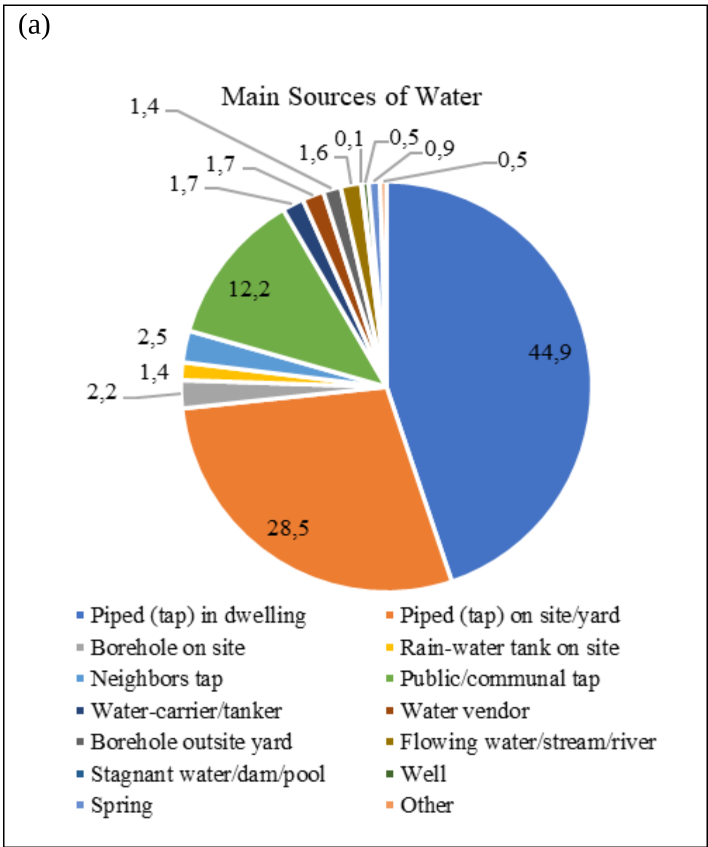
Figure 2-2: Map of the number of people living in poverty in South Africa (CSIR (StepSA), 2015)

**The following legend applies: Poor (R0 - R54 344 income per annum) Low emerging middle class (R54 345 - R151 727 income per annum); Emerging middle class (R151 728 - R363 930 income per annum); Realised middle class (R363 931 - R631 120 income per annum); Upper middle class (R631 121 - R863 906 income per annum); Emerging affluent (R863 907 - R1 329 844 income per annum); Affluent (R1 329 845+ income per annum*

2.1.1. Basic Services in South Africa

The provision of basic services such as electricity, shelter, water, sanitation, and waste removal services further describes the country's profile. Data for the provinces of Western Cape (WC), Eastern Cape (EC), Northern Cape (NC), Free State (FS), KwaZulu-Natal (KZN), North West (NW), Gauteng (GP), Mpumalanga (MP) and Limpopo (LP) from the 2019 General Household Survey, which forms the latest survey conducted, is presented in this section.

The access to clean drinking water is a fundamental basic need. According to StatsSA (2019), 88.2% of households had piped or tap water access in 2019. Figure 2-3(a) and (b) present the percentages of the different water sources used in various provinces of South Africa. These sources vary significantly between provinces, as noticed in Figure 2-3(b). The main drinking water source is piped (tap) water either in a dwelling (44.9%) or on-site/yard (28.5%). In 2018, water tankers or wells were used as alternative sources due to water interruptions longer than two days, attributing to the higher percentage (see Figure 2-3 (b)). Overall, most parts of the country have some water source.



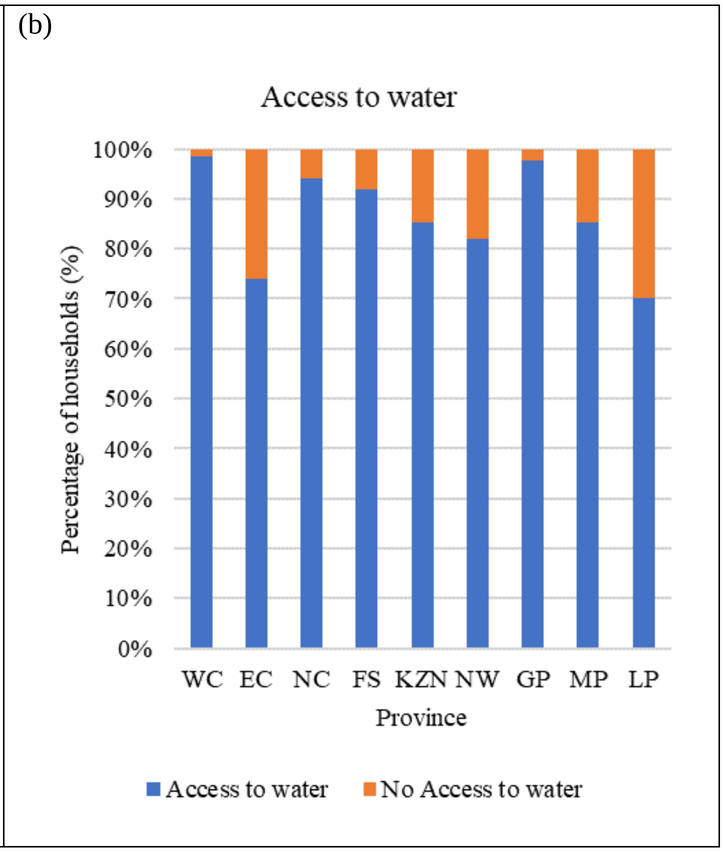


Figure 2-3: Percentage of (a) the main source of drinking water and (b) households with access to tap or piped water for each province in South Africa (plotted with data from StatsSA, 2019).

The percentage of households with and without electricity connections is presented in Figure 2-4 (a). Overall, GP and WC have the most households without electricity connection, with EC and KZN closely following. The influx of people to city regions usually results in many informal settlements, possibly influencing access to basic services. The primary household sources of energy are connected electricity supply (85.0%), wood (7.8%), and paraffin (3.9%) in 2019, as presented in Figure 2-4 (b) (StatsSA, 2019). Furthermore, wood is commonly used in rural provinces such as MP (16.7%) and LP (32.1%). According to StatsSA (2019), some households (24.9%) preferred the use of gas (4.2%), and paraffin (3.9%), rather than grid electricity. The main energy source was electricity in all provinces except for NC, where gas was preferred.

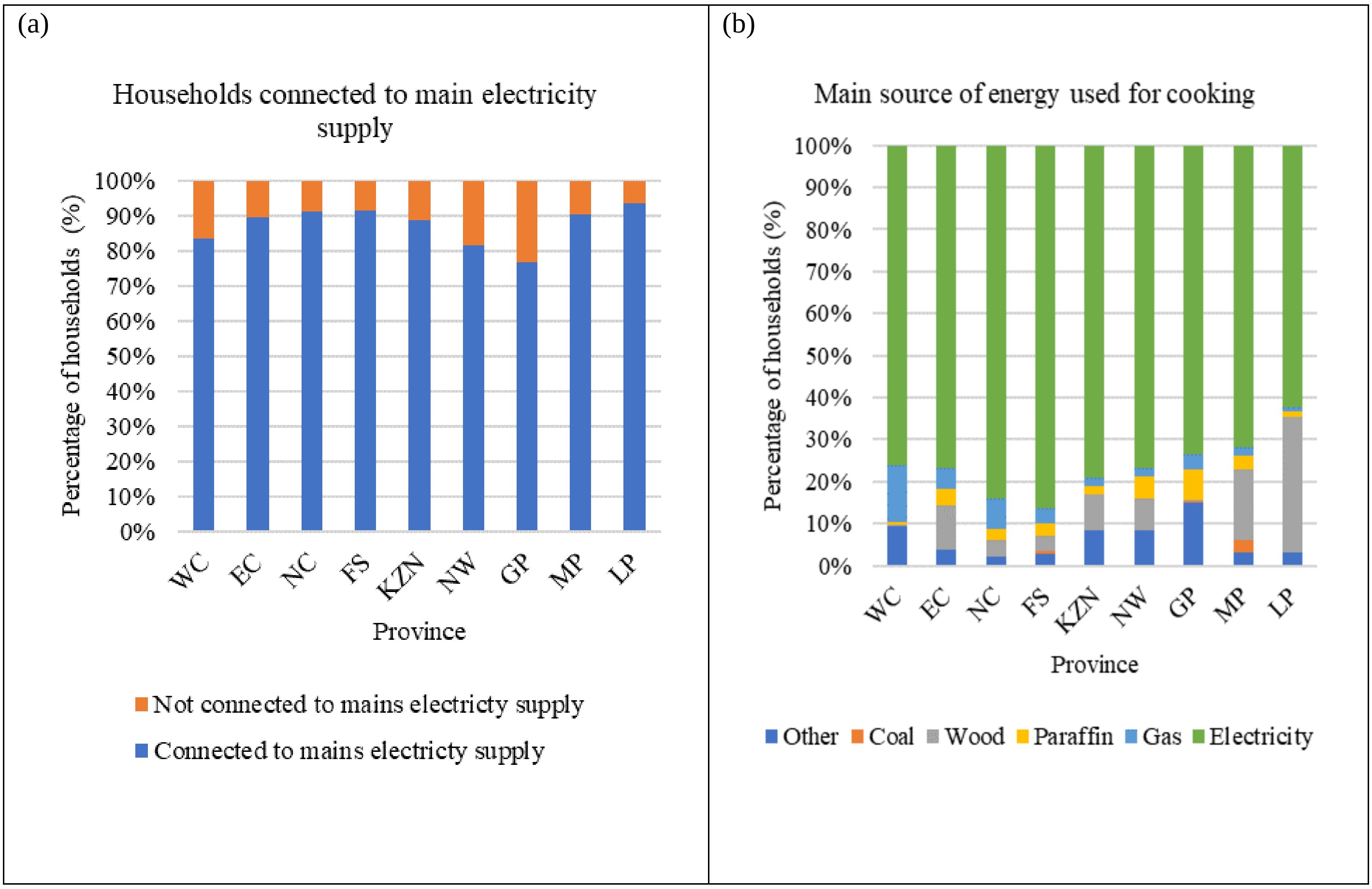


Figure 2-4: The percentage of households (a) with electricity supply and (b) the different types of the main source of energy used for cooking in the different provinces (plotted with data from StatsSA, 2019).

The provision of adequate sanitation and toilet facilities are presented in Figure 2-5 (a) and (b). Overall, 82% of households in South Africa received adequate sanitation in 2019. The most households lacking adequate sanitation were in LP (36%) and NW (31%). However, the NC has the most households without serviced toilet facilities. At the same time, the WC and KZN were found to have the most households with adequate sanitation and toilet facilities, respectively. The levels of sanitation are attributed to urbanisation, rapid household growth, and the preference for flush toilet systems. However, StatsSA (2019) acknowledged that water shortages and supply interruptions are experienced in many parts of the country, promoting alternative sanitation sources.

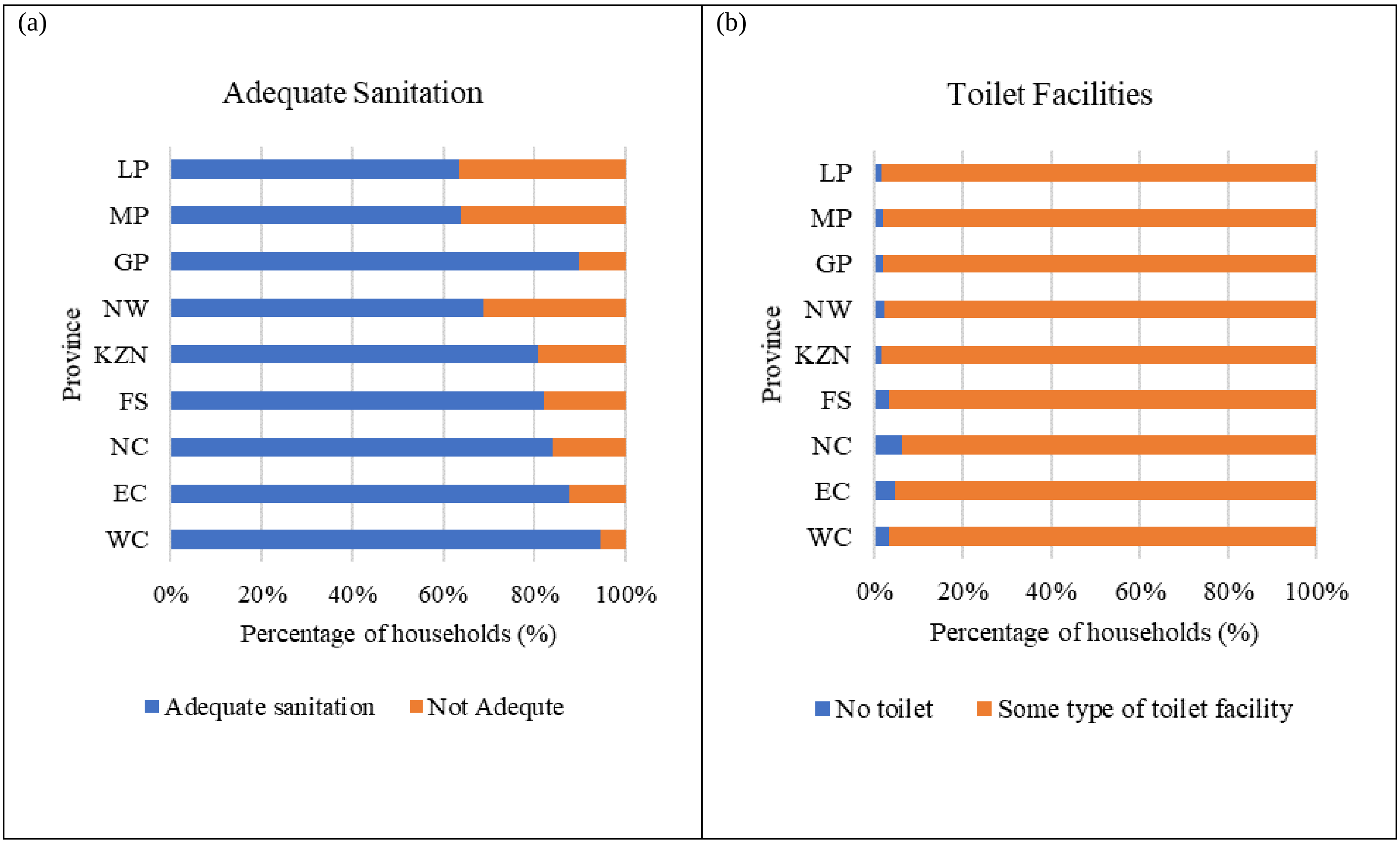


Figure 2-5: The percentage of households with (a) adequate sanitation and (b) toilet facilities in the different provinces of South Africa (plotted with data from StatsSA, 2019)

The different types of dwellings, namely formal, informal, traditional, and other, are presented in Figure 2-6. Predominately, formal dwellings are most common throughout the country. Informal housing types are the second most commonly found except in KZN and EC, with many traditional dwellings. The type and location of dwellings usually affect the types of waste and services provided by municipalities.

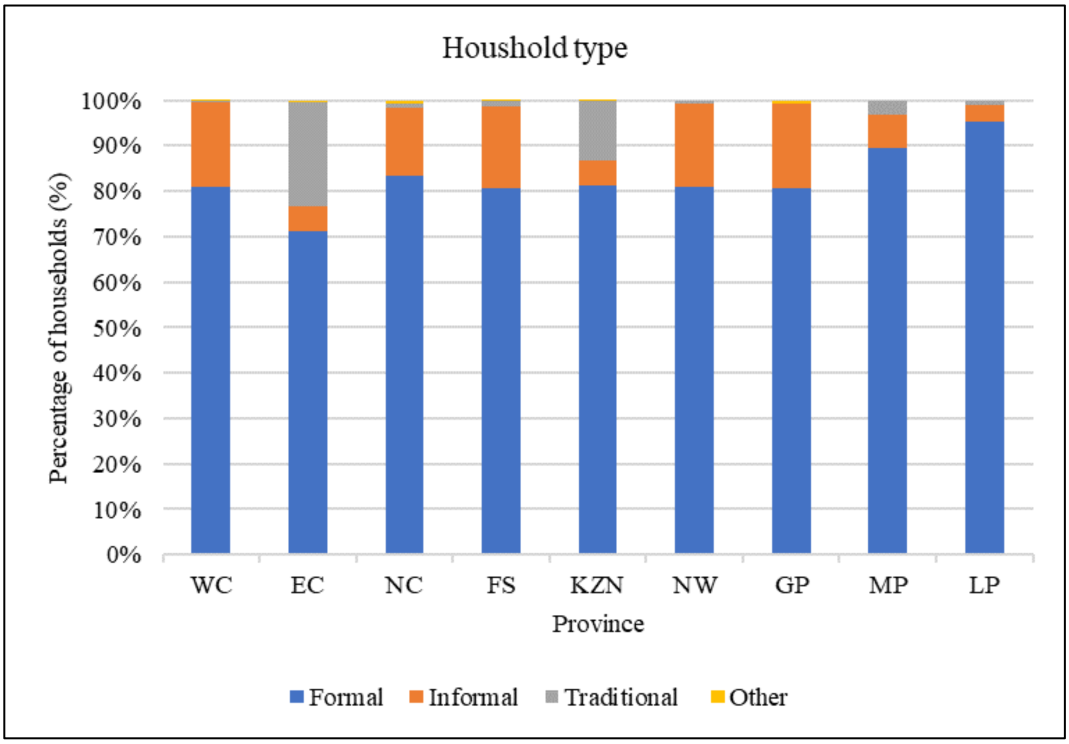


Figure 2-6: The percentage of different household/dwelling types for the different provinces (plotted with data from StatsSA, 2019)

2.1.2. Composition of Waste in South Africa

Similar to other basic services in South Africa, the country's waste disposal services also vary. According to StatsSA (2019), the available waste data in the public domain in South Africa consists primarily of landfilled waste. Little information exists on improperly disposed waste, leading to a gap in quantifiable rural waste data for areas lacking service delivery.

The DEA published South Africa's waste profile in 2011 and updated it in 2017 (State of Waste Report – SoWR) as part of the National Waste Management Strategy (NWMS) action plan (DEA, 2018a). It aimed to estimate all general waste generated in South Africa, either collected at kerbside or brought to the landfill for disposal. For this study, uncollected waste (that is, waste not collected at curbside or taken to a landfill) was not included; thus, the total waste produced at a country level can be assumed to be much greater than that represented in the SoWR (Figure 2-7 (a)).

Based on data from the different provinces, the SoWR accounted for 108 Mt of MSW per year, of which 59 Mt of general waste was generated in 2017. Of the general MSW waste, only 10% was recyclable, and 53.1 Mt was sent to landfill. The total general waste was considered municipal (4.8 Mt) and commercial and industrial waste (3.5 Mt). The most significant waste stream was organic waste (30.5

Mt), and the lowest was tyres (0.24 Mt) (DEA, 2018). The report stated that 38.3% of total general waste was recycled; of this, the highest fraction was organic waste (45.7%), and plastics were the lowest (2.3%), as presented in Figure 2-7 (b) (DEA, 2018a).

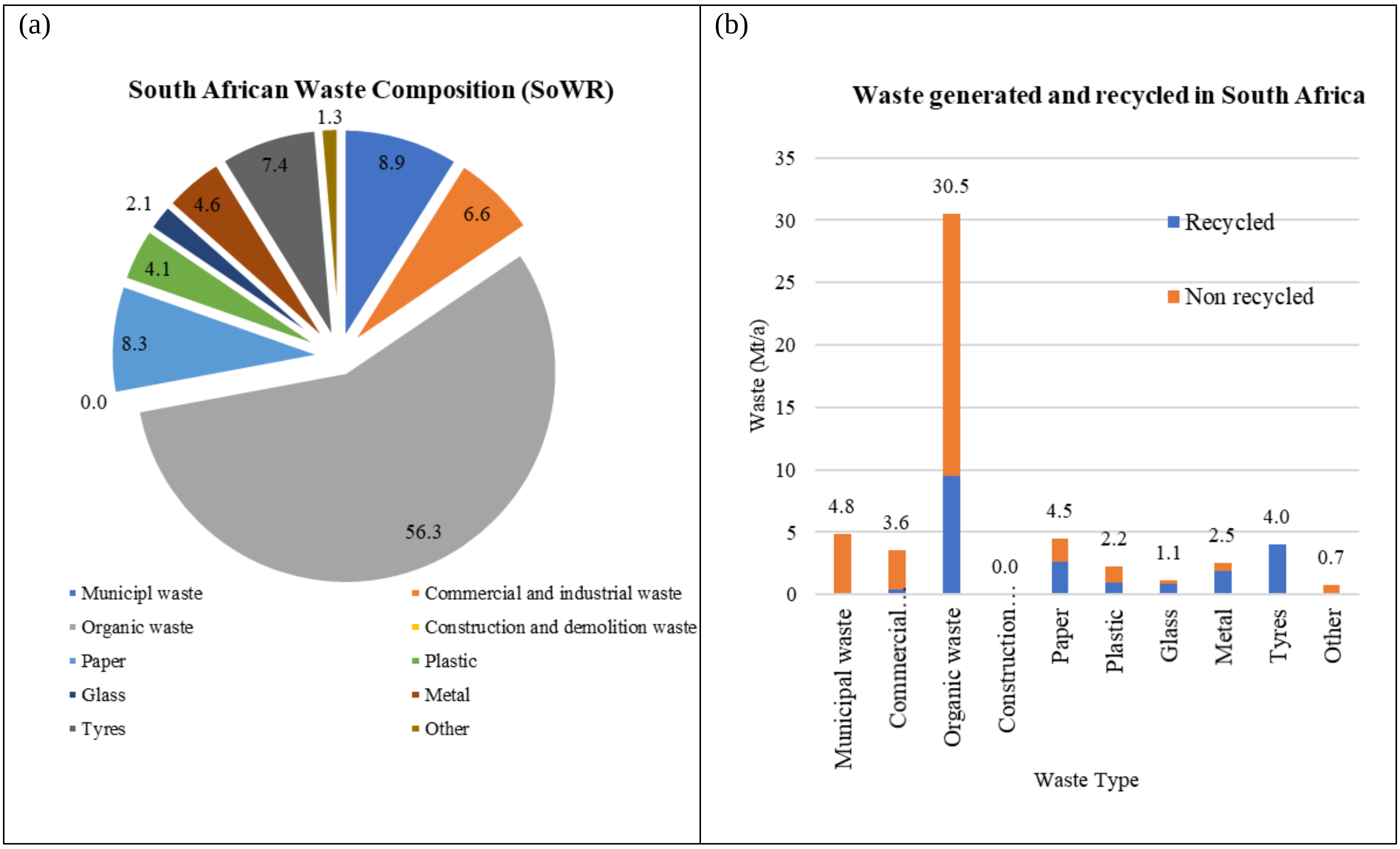


Figure 2-7: South African country level (a) general waste composition in wt% and (b) the recycling and recovery rate for each type of waste according to the SoWR for serviced households (plotted with data from DEA, 2018a)

2.1.3. Waste Disposal

Waste collection and transportation is one of the most costly waste management aspects, with many municipalities struggling to provide waste collection services timeously. In the 2019 General Household Survey, the predominant disposal method was “own refuse dump” (84%) in rural areas, with only about 8% of households receiving waste collection services at least “once a week”, as presented in Figure 2-8 (Stats SA, 2019). Contrary to this, urban and metro areas received high levels of waste collection, with a “once a week” collection rate of about 75% and 83%, respectively (Stats SA, 2019).

The Department of Environmental Affairs (DEA) (2018) estimated a 2 million household backlog of solid waste service provision, with some 900 000 households not receiving any service. It is further estimated that 82% of rural households rely on their refuse dump compared to 10.6% in urban areas and

4.5% in metro areas (most likely in informal households) (DEA, 2018). Communal dumps were prevalent in all dwellings, and dumping waste anywhere was mostly found in rural settings. Nationally, 25% of formal dwellings, 90% of traditional dwellings, and 35% of informal dwellings received no waste management, using uncontrolled refuse dumps or dumping waste anywhere (APWC, 2020).

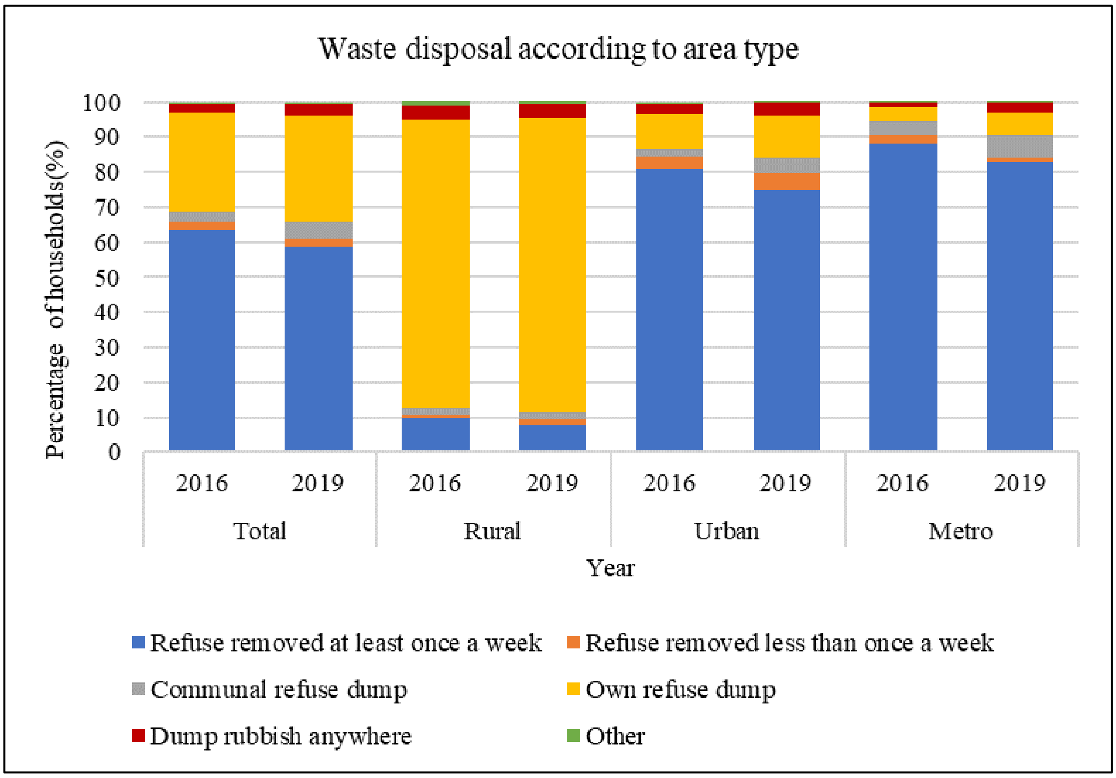


Figure 2-8: Waste disposal in different area types in 2016 (DEA, 2018) and 2019 (Stats SA, 2019)

Nahman (2021) found that the dominance of landfilling in South Africa can be grouped into six categories: legislative barriers, low cost of landfilling, high cost of alternative waste management options, inadequate funding and resources, the perceived lack of benefits of alternative options and behavioural and institutional issues. Nahman (2021) further proposed that the main reason for landfilling waste in South Africa is the low disposal costs, with the common understanding that landfilling is under-priced within the country.

2.1.4. Waste collection costs and gate fees

Waste must be collected from households and transported to landfill sites for storage. Once the waste is collected, it is of little value at landfills, and instead, the waste fractions of interest could be collected from landfills and beneficiated. The waste collection and disposal costs (sometimes called landfill tax) vary between provinces in South Africa. A survey by Simelane (2016) found the monthly waste removal tariffs in 2016 ranged from R34 to R225/month in 2015/2016, based on the waste characteristic. Table

2-1 presents the costs of collecting and removing household waste for 2016 (Simelane, 2016). This fee is paid by households monthly and results in waste disposal at landfill sites.

Table 2-1: Waste collection and disposal tariffs for different cities in South Africa in 2015/2016 (Simelane, 2016)

Municipality	Household waste collection fee	Waste disposal fee
City of Tshwane	R221.96 per m^3	
City of Johannesburg	R104 to R225.21 per month	R180.18 per ton
City of Cape Town	R118.50 per month	R395.00 per ton
eThekwini	R33.75 to R165.03 per month	R174.40 per m^3
Ekurhuleni Metropolitan	R89.56 to R225.15 per month	R224.29 per ton

According to GreenCape (2020), South Africa has lower waste disposal costs than developed economies (GreenCape, 2020). Gate fees are the amount the municipality charges to dispose of waste at the facility. They are a once-off payment for the waste's storage and/or treatment. The 2019/2020 landfill gate fees across all eight of South Africa's metros were published by GreenCape, represented in Table 2-2. The average landfill gate fee has increased substantially over the past five years, which can be attributed to the decline of land space in the country (GreenCape, 2020). A comparison between Table 2-1 and Table 2-2 notes an increase in waste disposal/gate fees in respective municipalities between 2016 to 2020. As such, the household waste collection fees are also expected to have increased. However, no recent data was readily available at the time of this study to determine the exact increases. Table 2-1 serves as a general indication of differing waste-associated costs in different municipalities in South Africa.

Table 2-2: The landfill gate fees of general waste for metropolitan cities in 2019/20 (GreenCape, 2020)

Location	Waste disposal fee/gate fee (2019/20)(R/t)
City of Tshwane	R230
City of Johannesburg	R267
City of Cape Town	R584
eThekwini Municipality	R417
Ekurhuleni Metropolitan Municipality	R301
Nelson Mandela Bay	R176
Mangang	R370

2.1.5. Waste Hierarchy

The waste hierarchy, encompassing the '3R' concept (Reduce, Reuse and Recycle), is widely accepted globally, being extended by the fourth 'R' (Recovery) as described in the NWMS 2020 (UNEP, 2010; Das et al., 2019; DEFF, 2020a). This concept promotes waste reduction, circular economy principles, cleaner products, and waste valorisation by transforming energy and materials (Abdel-Shafy and Mansour, 2018; Sakai et al., 2017; DEA, 2020). The diversion of waste from landfills and drive towards a circular economy promotes the closed-loop of materials through reuse, recycling and recovery (Strydom, 2018). Sustainable goal number 12 of the South African National Development Plan (NDP) further promotes the absolute reduction of landfill waste disposal. It increases waste reuse, recycling, and recovery (Viljoen, et al., 2021). The NWMS sets targets for diverting recyclables away from landfills, and these targets are further enshrined in the EPR regulations, discussed further in section 2.3.4. The inverted pyramid waste hierarchy is presented in Figure 2-9.

The foundation of the waste hierarchy is waste avoidance and reduction, where goods are designed to minimise waste components or substitute them with more benign materials (DEFF, 2020a). An example is the replacement of styrofoam fast-food packaging with waxed paper packaging. The next stage of the hierarchy concerns reuse, which reduces waste generation. An example is the standardisation of bottles, allowing them to be washed and refilled rather than remelt the glass to manufacture new bottles. Recycling follows reuse and involves processing waste into raw materials. An example is the before-mentioned glass remelting, or the generation of plastic pellets from recyclate, which can then be used to produce new products. Finally, recovery from solid wastes describes the collection of specific waste fractions from mixed solid waste such as aluminium, plastics, and steel cans, followed by recycling. Alternatively, some fractions may be used to reclaim their energy content (e.g. gasification or incineration) (DEFF, 2020a).

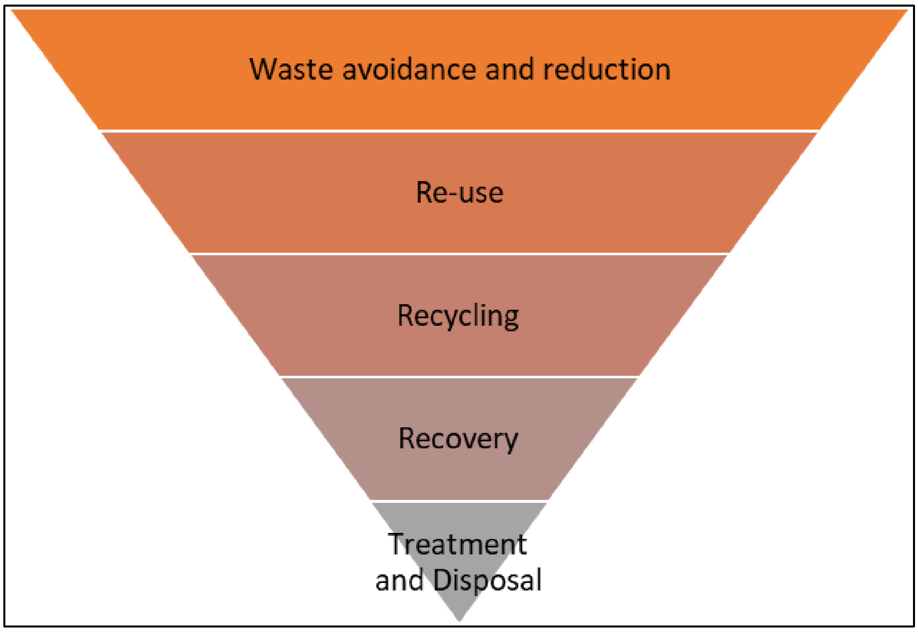


Figure 2-9: The waste hierarchy expressed in an inverted pyramid (adapted from DEFF, 2020a)

2.1.6. Recycling in South Africa

According to Godfrey and Oelofse (2017), the South African recycling industry has grown successfully. South Africa has established policies to promote waste diversion from landfills. Still, household participation is voluntary in South Africa, either through a curbside collection of separated waste or taking recyclables to buy-back or drop-off centres.

According to StatsSA (2019), waste was predominately not separated in 2019. Between 64% (Cape Town) to 95% (eThekwini) of the households do not participate in household recycling, Figure 2-10. Sorting of waste by waste pickers (orange bar representing "waste pickers sort themselves" by StatsSA) was more common in Cape Town (16%), Johannesburg (14%), and Mangaung (14%) as compared to eThekwini, with the lowest percentage of 0.7%. It is assumed that this represents waste separation before reaching landfill sites. Waste separation to support waste pickers was highest in Ekurhuleni (6.1%) and lowest in Buffalo City (0.5%). Recyclables taken to drop-off centres were highest in Cape Town (4.8%) and lower than 1% in eThekwini, Buffalo City, Tshwane, and Mangaung. The collection of waste by recycling companies was prevalent in Cape Town (13%), with all other municipalities falling below 5%.

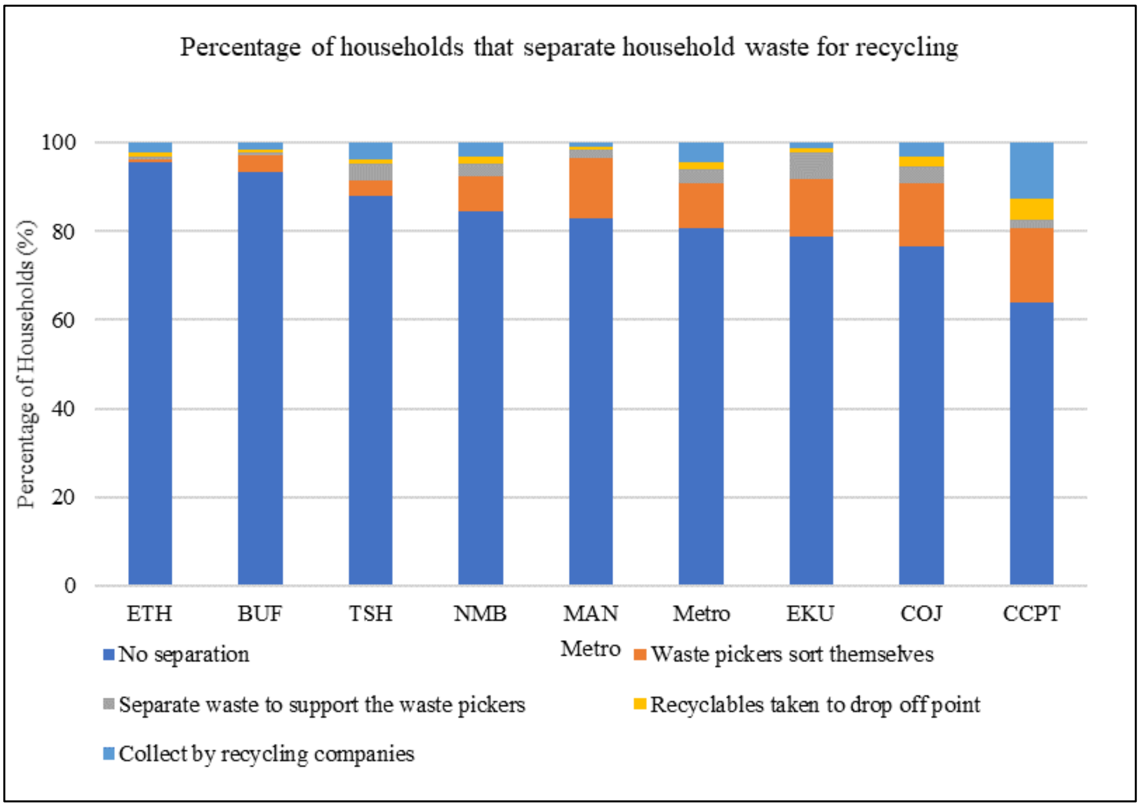


Figure 2-10: Households that separate their waste for recycling in 2019 (plotted with data from Stats SA,2019)

***Abbreviations for metropolitan areas in Figure 2-10 are as follows: ETH – eThekwini, BUF: Buffalo City, TSH: Tshwane, NMB: Nelson Mandela Bay, MAN: Manguang, Metro: Metropolitan, EKU: Ekurhuleni, COJ: City of Johannesburg, CCPT, City of Cape Town*

The recycling sector relies highly on the informal sector of waste pickers and reclaimers who, in many instances, are driven by social needs. The informal sector collects recyclables from either landfill sites, dumpsites or curbside (household, commercial or communal bins) in the country (APWC, 2020). However, informal waste pickers in rural areas suffer from unpredictable activities such as uncertain waste collection provided by municipalities and varying waste generated by households. Waste pickers take their recyclables to buy-back centres (BBCs) which are vital to the value chain (Yu et al., 2020; Viljoen et al.,2019). A diagram of the waste value chain is illustrated in Figure 2-11. In Durban, BBCs provide trucks on specific routes where waste pickers can sell their recyclables (Viljoen et al., 2019). The prices of different recyclables were found for 2011 by the study conducted on the BBCs by Viljoen et al. (2019), presented in Table 2-14.

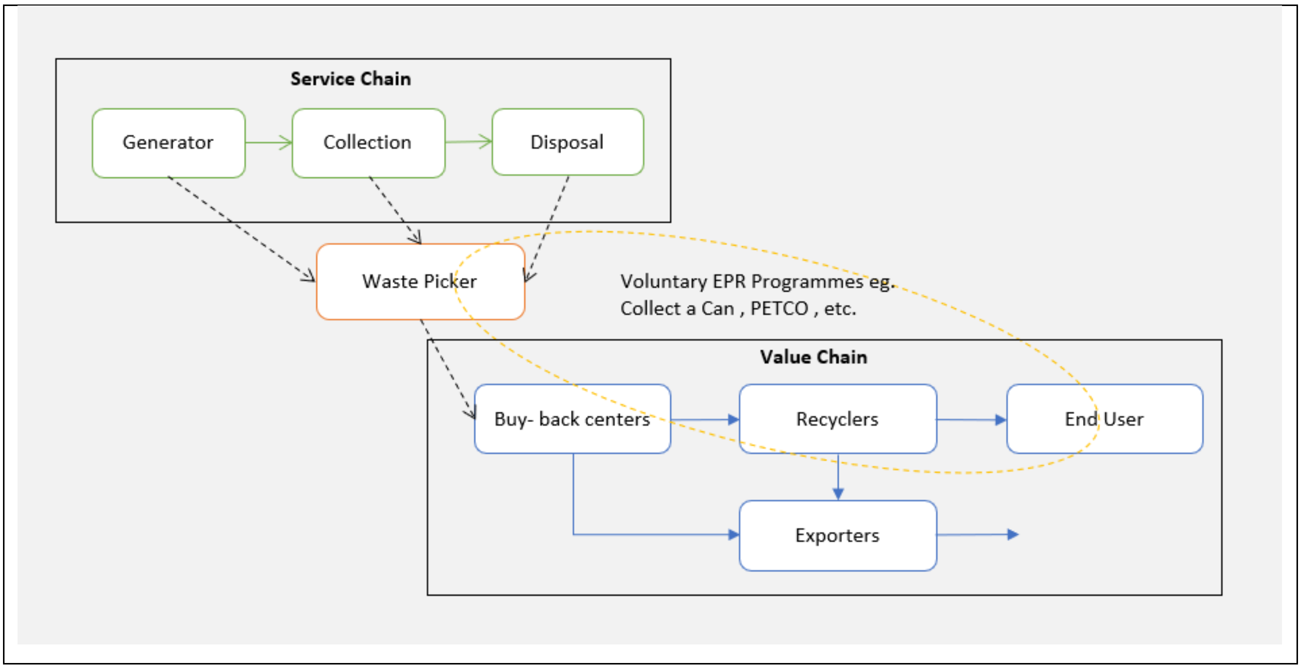


Figure 2-11: The typical role of informal waste pickers in the waste value chain in South Africa (according to Godfrey, et al., 2016)

2.2.Environmental Considerations

The improper management of waste contributes to pollution, climate change and directly affects many ecosystems and species. The landfilling of waste releases methane created through biodegradation, and poorly designed landfills lead to water and soil contamination. The GHGs that contribute the most to global warming are carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (NO_x), released during the management and disposal of wastes. However, although low, waste collection and transportation also contribute to overall emissions from waste management (Friedrich & Trois, 2010). For example, South Africa's waste sector contributes to about 4.3% of GHG emissions and 37% of total methane emissions. Couth and Trois (2012) illustrated that GHGs emitted from waste may be reduced through mechanical biological treatment.

Friedrich and Trois (2011) investigated the amount of GHG produced by different waste treatment options in developed and developing countries and found that the highest GHG savings were achieved through recycling. The amount of GHGs produced is dependent on the treatment process. Combustion of waste can produce many GHGs, up to 371 kg/ton, while AD processes in developed countries save on GHGs (-210kg/ton) (Friedrich and Trois, 2011). Thus alternative treatment methods may assist in the reduction of GHGs.

2.3.Legislation in South Africa

South Africa has complex waste regulations, strategies, and legislation in place. Some legislation relating to waste will be explained in detail in this section. Navman (2021) found that legislation and policy initiatives are fragmented and perceived to be uncoordinated in South Africa.

2.3.1. National Waste Management Act (NEM: WA)

The NEM: WA was first enacted in 2008, with revisions in 2013 and 2014. It promotes integrated waste management planning and regulates norms, standards, and compliance with the South African Waste Information Centre (SAWIC).

Minimum requirements are set for anyone who undertakes an activity that generates or handles any waste, identified in three categories of waste which require different licensing requirements based on the type of activity and processing quantities. The development of municipal waste management infrastructure requires environmental authorisation based on the category (DEA, 2011):

- Category A: General waste treatment between 10 to 100 tons/day, i.e., composting facilities, requires a basic assessment (takes about 199 days);
- Category B: General waste treatment above 100 tons/day, i.e., landfills, anaerobic digestion and direct combustion, requires a full Environmental Impact Assessment (EIA) (which takes about 216 days); and
- Category C: material recycling, waste transfer stations, drop-offs, crushing and builders rubble requirements are specified by norms and standards for specific waste types or treatment options. For example, the National Norms and Standards for Disposal of Waste to Landfill relates to landfilled waste.

NEM: WA has adopted the internationally recognised waste hierarchy, prioritising waste avoidance and placing disposal as the last option (DEA, 2011). Therefore, based on the facility size, all treatment and recycling activities of interest in this study require licencing according to NEM: WA.

2.3.2. National Waste Management Strategy (NWMS)

The NWMS was first enacted in 2011 and most recently amended in 2020. According to section 6(3) of the NEM: WA, the state is responsible for reducing waste generation and promoting reuse, recycling, and recovery in an environmentally sound manner. The NWMS 2020 provides a clear framework and strategy for implementing the NEM: WA and outlines the government's plans and policy to ensure that waste management is "equitable, inclusive, sustainable and environmentally sound" (DEFF, 2020a).

The NWMS 2020 contains three strategic pillars. The expected outcome of pillar one is to prevent waste and ensure 40%, 55% and at least 70% of waste diverted from landfills in five, ten and 15 years (DEFF, 2020a). Pillar two outlines financially sustainable and clean waste management services. The third pillar focuses on enforcing compliance and zero tolerance of pollution, litter and illegal dumping (DEFF, 2020a).

Another aim of the NWMS 2020 is to promote separation at source by increasing public awareness and government and private sector investment and, where feasible, economic incentives (DEFF, 2020a). The NWMS 2020 encompasses the Ellen MacArthur Foundation's circular economy and advocates closing the loop. One drawback of the NWMS 2011 and 2020 is that although waste diversion targets had been set, no clear roles and responsibilities were established, resulting in a halt from industry and government (Nahman, 2021).

2.3.3. Municipal Systems Act (MSA)

According to the Municipal Systems Act (MSA), project developers must follow strict procurement procedures, including waste management projects. Furthermore, detailed feasibility studies (expensive and time-consuming) are required to identify and allocate money within the municipality (GreenCape, 2016). The lack of coordination between government departments on thresholds and timeframes can result in additional unplanned costs (GreenCape, 2016).

2.3.4. Extended Producer Responsibility

The Amended Regulations and Notices Regarding Extended Producer Responsibility (EPR) was published in 2021 (DEFF, 2021). Together with the EPR Regulations (DEFF, 2020b) , the Notices for electrical and electronic equipment (DEFF, 2020c), lighting (DEFF, 2020(d)) and paper, packaging and some single-use products (DEFF, 2020(e)) currently apply to EPR schemes.

"Extended Producer Responsibility is defined as a producer's responsibility to ensure that the management is extended to the post-consumer stage of an identified product's life cycle" (DEFF, 2021). The regulation provides a framework for the producer to adhere to regarding the development, implementation, monitoring and evaluation of EPR schemes (DEFF, 2020b). All producers must be members of an approved EPR scheme that addresses, among other things: waste collection, waste processing, beneficiation and disposal, detailed data collection and reporting against targets, mandatory take-back of all identified products at the end of life and differentiated EPR fees based on weight and recyclability.

In addition, EPR is a crucial intervention aimed at supporting the goals of the NWMS to increasingly divert waste from landfills, with the long-term goal of zero-waste to landfill, as expressed above. Targets for each identified waste stream are published in the annexures of the respective documents. Waste collection is assumed to increase significantly over the coming years. A key question would be whether urban waste management will fulfil these requirements, and if not, at what stage will rural communities be considered. The EPR recycling targets for streams of interest are given in Table 2-3.

Table 2-3: EPR recycling targets from years one to five (DEFF, 2021)

Year	**1**	**2**	**3**	**4**	**5**
Glass (all)	38	43	48	53	54
Metal Aluminium (non ferrous cans)	30	32	33	34	35
Plastic Polyethylene Terephthalate (PET) Beverage bottles	54	58	59	61	65
Plastic PET Oil Bottles	6	12	23	29	35
Plastics thermoformed PET	8	12	17	24	30
Plastic PET (Flexible)	9	18	27	36	45
Polyvinyl Chloride (PVC) (Rigid and flexible)	5	5.5	6	6.5	7
Polystyrene (PS) (expanded and high impact)	20	25	30	36	43
Newspapers	35	40	45	50	55
Magazines	33	34	36	38	40
Office and graphic paper – mixed and other paper	58	63	68	73	80
Corrugated cases/ kraft papers	58	63	68	73	78

EPR amendments outline the producer's specific roles and responsibilities and aim to enforce proper record keeping and monitoring of these regulations (DEFF, 2021). To this extent, EPR can assist in waste management facilities where they lack, such as in rural communities. Furthermore, the EPR regulation instructs that the PROs should, amongst other criteria, co-operate with municipalities to increase the recovery of identified products from municipal waste and collaboratively utilise new and existing infrastructure, integrate informal waste collectors/reclaimer or pickers (DEFF, 2021). This will promote waste collection services, enhance current practices, or provide services that cannot meet the EPR schemes' targets.

2.3.5. National Organic Waste Composting Strategy

The strategy aims to promote composting facilities and eliminate a waste management license. The strategy was formed to display the potential benefits of composting as a waste diversion option (Godfrey, et al., 2018). The DEFF is currently updating the draft national norms and standards for composting, excluding organic waste composting facilities that process exceeding 10 tonnes of organic waste a day from a waste management licence (DEA, 2013). The "best practice" for composting should be outlined and promote minimising negative impacts.

2.3.6. NEM: Air Quality Act

The National Environmental Management: Air Quality Act (NEM: AQA), established in 2004, provides national norms and standards regarding the regulation, monitoring, management and control of air quality. The act includes a list of activities that trigger air emission licensing processes. The NEM: AQA applies to WTE projects (such as anaerobic digestion and thermal treatment operations) where investors interested in these activities must consider the appropriate regulations and licencing requirements.

2.3.7. National Policy on Thermal Waste Treatment of General and Hazardous Waste

The policy provides a framework for thermal waste treatment technologies in South Africa. In addition, it considers the (i) incineration of general and hazardous waste (including but not limited to pyrolysis and gasification) and (ii) co-processing of selected general and hazardous waste (DEA, 2009). This policy loosely defines thermal treatment and incineration with no clear declination of pyrolysis and gasification processes. These are inherently less problematic technologies and should not be classified as incineration. The department aims to provide efficient and integrated procedures for environmental legislative requirements for thermal waste treatment, such as environmental authorisation, air emission licences, and waste management licences according to NEMA, NEM: WA and NEM: AQA (DEA, 2009). The act further supports implementation, develops necessary legislation, and provides guidelines, including the best technology and environmental options and norms and standards for the thermal treatment of waste.

2.3.8. Carbon Tax Bill

The Carbon Tax bill came into effect in June 2019 to aid the National Climate Change Response Policy of 2011 (NNCRP) in achieving GHG reduction commitments (National Treasury, 2019). Carbon emissions fall into three different scopes, namely: scope one (direct emissions such as emissions from combustions of stationary and mobile fuel sources directly from processes), scope two (emissions associated with purchased electricity- in most cases from Eskom), and scope three (indirect emissions from downstream processes from activities such as waste disposal, employee commute, etc.). The current emissions taxed include only scope one emission, thus excluding emissions from waste activities (which fall under scope three). However, some waste management projects that reduce carbon emission can apply for a carbon offset allowance that reduces tax viabilities by 5% to 10% of total emissions. GreenCape (2020) believes that the Carbon Tax will positively affect the waste sector by promoting waste disposal and treatment, enabling industries that recover heat/electricity from waste to benefit from offsets and waste projects to benefit from carbon credits.

2.3.9. Summary

From the current legislative framework in South Africa, it is clear that strides have been taken towards a more inclusive waste management system. There are multiple stakeholders who, together with the government, can move towards a zero-waste landscape sooner, as seen in EPR interventions.

The waste management hierarchy is supported by NEM: WA and NWMS. The NWMS 2020 promotes the circular economy, encouraging the waste hierarchy (Nahman, 2021). The production and handling of waste are deeply correlated to the country's environmental health, as seen in the applications of the NEMA: WA, NWMS and NEM: AQA. However, the municipalities (considered custodians of waste) play an enabling role in expediting or hindering waste projects under the MSA. In the absence of EPR schemes, producers generally do not take responsibility for the waste generated by the products they put on the market; managing this waste becomes the municipality’s problem. The government has developed norms and standards for handling particular wastes to aid proper uses. With the current drastic climate changes, the carbon tax can be used as a vehicle to reduce GHGs and promote Clean Development Mechanism (CDM) projects for waste in the country.

2.4. Waste Profiles of Selected South African Municipalities

To further understand the differences in the waste profile throughout the country, three municipalities were selected to exhibit the waste volumes and compositions: Calvinia, Garden Route District, and eThekwini. These waste compositions are expected to vary in amount and composition compared to the country profile represented in section 2.1.2.

2.4.1. Calvinia

Nell and Schenck (2018), within the Clean Cities Project funded by DST/CSIR/NRF, conducted a waste management study to quantify potential waste generation in Calvina (Namakwa District, Northern Cape). Forming part of the Hantam municipality (21 578 people), Calvinia had 9 680 people in 2011, living in 2 590 households, with about 56% in lower-income areas, 12% in middle-come areas and 32% in high-income areas (Frith,2011; Nell and Schenck, 2018). A map of the Hantam Municipality is given in Figure 2-12.

Concerning service delivery, it is noted that 65.2%, 95.9%, 80.5%, and 97.5% of households had access to piped water, electricity for lighting, flush toilets (sanitation services) and weekly refuse removal, respectively (Stats SA, 2012). According to the local municipality, formal waste removal services are provided at least weekly through a door-to-door collection or communal waste receptacle taken to the local landfill, which is permitted to receive 25 to 150 tpd of waste. The Calvinia landfill employs unskilled workers on a two-week rotational schedule to tend to landfill operations, limited to collecting litter outside the boundary (Nell and Schenck, 2018).

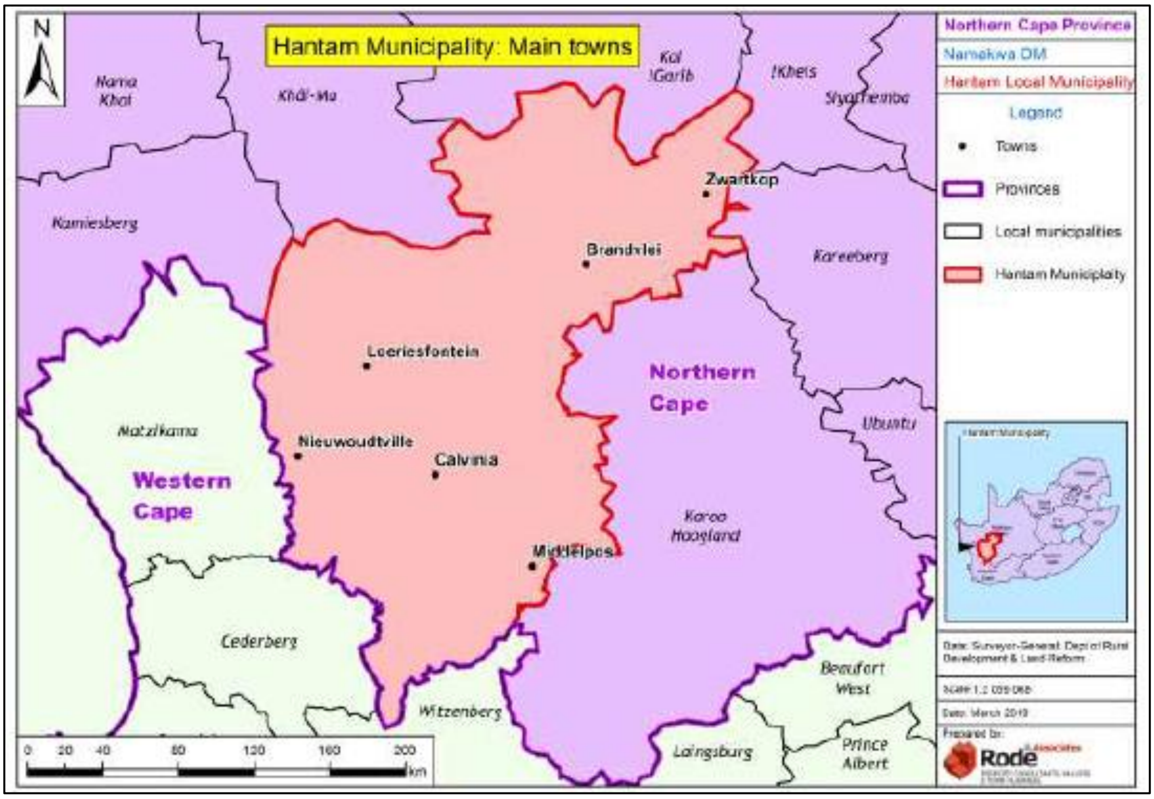


Figure 2-12:Map of Hantam Municipality showing main towns, including Calvinia (Hantam Municipality, 2020)

A Calivina Zero Waste (CZW) project funded by Tierhoek Boerdery and KLK Landbou aimed to minimise waste at landfills (Nell and Schenck, 2018). The main goal of separation at source was to utilise clear bags, and normal black bags refuse on collection days. The clear bags containing recyclables are collected independently to sort at the Material Recovery Facility, much like eThekwini (Nell and Schenck, 2018). Some forms of recycling are already evident in the area with the collection of glass, some plastics, and scrap metals, with the main challenge of storage space and distance to markets for recyclable goods (Nell and Schenck, 2018). In some informal settlements in Calvinia (Blikkiesdorp), residents state that the reliability of refuse services in these areas is low, and waste is usually taken to the veld for disposal (Nell and Schenck, 2018). Currently, there is no access control or revenue generation at the landfill site (Nell and Schenck, 2018). The closest buyer markets (Cape Town, Springbok, Upington and Beaufort West) for recyclables are about 400km from the Hantam municipality (Viljoen et al., 2021).

Nell and Schenck (2018) found that the annual waste generation in Calvinia was 1 600 tpa, meaning each resident generates on average 165.29 kg annually, 0.45 kg per person daily. This amount further translates to 1.81 kg of waste per 4-person household daily, which aligns with the national average of 2.00 kg of waste produced per household daily (Nell and Schenck, 2018). Table 2-4 presents the waste composition in weight and descriptions of waste fractions.

Table 2-4: Composition and description of major waste found in Calvinia (Nell and Schenck, 2018)

Waste Category	Composition (wt. %)	Major waste found
Garden waste	5.00	Sand, stones and leaves
Food/compost	27.98	Food scraps and inedible portions of food, cigarette butts
Glass	12.50	
Metals	4.00	Mostly beverage cans or food tins
Paper and cardboard	13.23	Cardboard packaging (cereal boxes), Tetra Pak-type packaging (milk) and newspapers. Little white paper and K4 cardboard
Polystyrene (PS)	0.80	Extruded PS, take away packaging
Non recyclable Plastics	3.73	Chips and chocolate wrappers, aluminium laminated PP, branded plastics
Recyclable Plastics	14.45	Mostly PET and LDPE
Others	5.54	Clothes, shoes and ash
E-waste	0.60	Electronic and electrical equipment such as batteries, cables, lighters, computer components and lightbulbs
Medical Waste	12.17	Sanitary pads and diapers

The waste weight and volume compositions are given in Figure 2-13 in a graphical form for easier comparison.

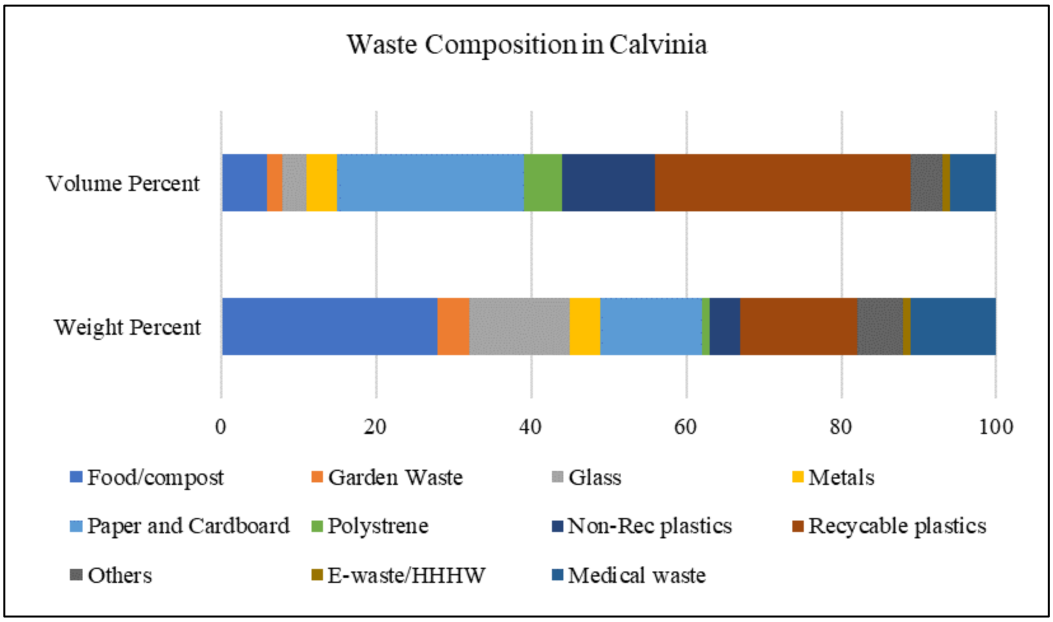


Figure 2-13: Waste composition by weight and volume in Calvinia (plotted with data from Nell and Schenck, 2018)

2.4.2. Garden Route District Municipality

The Garden Route District Municipality (GRDM) (previously Eden District) in the Western Cape consists of urban and rural areas in various municipalities. The local government institutions within the Garden Route District Municipality boundaries include Bitou, Knysna, George, Mossel Bay, Hessequa, Kannaland and Oudtshoorn municipalities. The spatial layout of the Garden Route District Municipality is provided in Figure 2-14.

The district contains about 150 informal settlements, with about 80% of the population residing in urban areas (Garden Route District Municipality, 2021). Inland areas are usually considered rural, with dispersed farming and small towns. These isolated dwellings sometimes result in high transport and social delivery costs due to their distance from facilities (Garden Route District Municipality, 2021). The GRDM population was 621 454 (2020), with an average of 27 901 people per investigated municipality (Garden Route District Municipality, 2021). Although the GRDM population grew at a rate of 0.45% between 2013 and 2020, the population statistics indicate that the population decreased between 2019 and 2020 (Garden Route District Municipality, 2021).

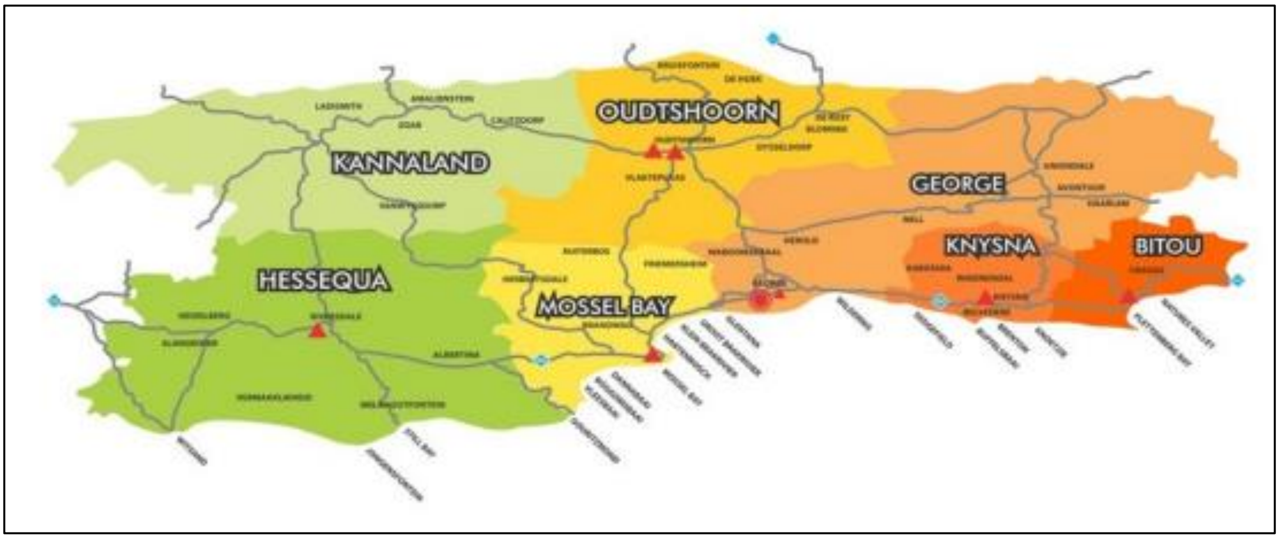


Figure 2-14: Map of the Garden Route District Municipality (Garden Route District Municipality, 2021)

The Bitou Municipality landfilled approximately 778 tpm waste, of which about 45% was recyclables (soft plastics, paper and cardboard, glass and metal) (Eden District Municipality, 2016a). The Hessequa Municipality estimated that 678 tpm waste was collected and transported to the landfill within the municipality, with seasonal variations (Eden District Municipality, 2016b). Approximately 38% of all waste is recyclables that could be diverted from the landfill, with informal waste pickers recovering recyclables at the Steynskloof site (Eden District Municipality, 2016b). Approximately 223 tpm of waste was collected and disposed of at the various landfill sites in the Kannaland Municipality, excluding waste from industry (including two large dairy industries) and unserviced households (Garden Route District Municipality, 2019 (a)).

The Knysna Municipality estimated monthly waste disposal of 1 276 tpm to the PetroSA landfill in Mossel Bay (Eden District Municipality, 2016c). About 41% of the waste can be considered recyclables. The monthly household waste was estimated at 2 307 tpm in the Mossel Bay Municipality (Eden District Municipality, 2016d). The waste contains 42% of recyclables, all of which is disposed of at the PetroSA landfill (Eden District Municipality, 2016d). The Oudtshoorn Municipality disposed of waste predominately at the Grootkop landfill site and estimated the monthly waste disposal of 912 tons, with about 36% recyclables (Eden District Municipality, 2016e). The George Local Municipality (GLM) generates about 4 846 tons of waste monthly, with domestic waste disposed of at the Uniondale and PetroSA landfill sites (GIBB Engineering and Architecture, 2019). All municipalities experience seasonal variations in waste, largely increasing in holiday periods (Eden District Municipality, 2016a-e; Garden Route District Municipality, 2019). Furthermore, some recyclable content is assumed to be contaminated by organics in waste. The waste profile of each municipality is presented in Table 2-5 and Table 2-6.

Table 2-5: Waste generation, number of households and daily waste generation for the different municipalities in the Garden Route District for 2016 (Eden District Municipality, 2016a-e; Garden Route District Municipality, 2019)

Municipality	**Bitou**	**Hesse-qua**	**Knysna**	**Mossel Bay**	**Kanna-land**	**Oudtshoorn**	**George**	**Total**
Monthly landfilled waste (tpm)	778	678	1 276	2 370	223	912	4 846	11 083
Yearly landfilled waste (tpa)	9 336	8 131	15 312	28 440	2 671	10 938	58 152	132 996
Population (2016)	54 427	54 524	72 511	93 475	24 931	98 332	203849	602 049
Per capita (kg/pp/day)	0.47	0.41	0.58	0.83	0.29	0.30	0.78	0.61

Table 2-6: Waste compositions of each local municipality in GRDM (Eden District Municipality, 2016a-e; Garden Route District Municipality, 2019)

Municipality	**George**	**Bitou**	**Hesse-qua**	**Knysna**	**Mossel Bay**	**Kanna-land**	**Oudtshoorn**
Soft Plastics (wt%)	8.2	7.2	5.8	8.0	10.7	10.7	6.5
Hard Plastics (wt%)	7.6	7.0	7.0	8.3	10.8	10.8	6.7
Paper (wt%)	5.3	9.2	6.6	7.4	7.0	7.0	8.0
Cardboard (wt%)	7.3	8.5	6.1	7.8	8.7	8.7	6.5
Glass (wt%)	7.3	9.7	8.1	6.3	9.8	9.8	6.2
Metal (wt%)	2.7	3.9	3.7	4.1	3.1	3.1	2.8
Food Waste (wt%)	24.7	29.9	32.0	25.1	15.1	15.1	22.6
Garden (wt%)	13.2	4.9	3.8	3.1	3.0	3.0	14.8
Textiles (wt%)	4.6	4.1	5.3	4.7	7.6	7.6	3.8
Wood (wt%)	1.9	0.4	0.9	0.8	0.2	0.2	0.8
Inert (wt%)	1.7	0.3	0.9	0.9	1.1	1.1	2.0
Nappies (wt%)	8.0	4.7	8.1	9.6	8.7	8.7	8.4
E-Waste (wt%)	0.3	0.5	0.3	0.3	0.1	0.1	0.3
Hazardous (wt%)	0.6	0.3	0.7	0.6	0.8	0.8	0.5
Rest (wt%)	6.7	9.4	10.5	13.1	13.3	13.3	9.9

There are no operational landfill sites in Bitou. The George local municipality has two active landfills: the George (Gwaing) landfill site and the Uniondale landfill site (planned closure to commence in 2019). There are seven operational landfill sites in Hessequa, while the Jongersfontein site has been developed into a drop off facility (closed and rehabilitated). There are four landfill sites in Kannaland, three of the four with operational permits. None of these sites has weighbridges, and data on waste tonnages entering the facility was recorded at two locations. The Mossel Bay Municipality has three operational landfills: Louis, Great Brak and PetroSA. The PetroSA landfill accepts mixed domestic waste from the Mossel Bay Municipality, Knysna Municipality, Bitou and George Municipality. Although domestic waste is received from the aforementioned local municipalities, it does not originate from all the sites within the local municipality. The Oudtshoorn Municipality has three operational landfill sites: Grootkop, De Rust and Dysseldorp (decommissioning to commence in 2019).

The PetroSA landfill accepts waste from four local municipalities in GRDM: George Local Municipality, Mossel Bay Local Municipality, Bitou Local Municipality, and Knysna Local Municipality. The amount of domestic waste deposited at the landfill reported for 2018/2019 was: 3 008.3 tpm from George, 2 390.1 tpm from Mossel Bay, 771.6 tpm from Bitou and 1 043.5 from Kysnsa (GIBB Engineering and Architecture, 2019 (a)-(d)). Based on this data, the total monthly domestic waste was 86 562.6 tpa and will be considered for further analysis.

The waste management tariffs for domestic customers for a single unit per month as stated in the waste management report as presented in Table 2-7.

Table 2-7: Waste management tariffs for domestic customers for 2019/2020 (single unit/ month) (GIBB Engineering and Architecture, 2020)

Municipality	Waste Management Tariff 2019/2020 (R/month)
Bitou	243.00
George	207.71
Hessequa	103.05
Knysna	103.25
Kannaland	219.32
Mossel Bay	190.31
Oudtshoorn	147.45

2.4.3. eThekwini

The eThekwini Municipality is located in KwaZulu-Natal and spans about 2.297 km^2 extending from Tongaat to the Umkomaas suburbs (Bosch Munitech, 2016). According to the eThekwini IDP, the forecasted population for 2021 is 4 004 603 people with 2 905 000 households (eThekwini Municipality, 2020). It is estimated that 60% of households in eThekwini are below the poverty line. The settlement dynamics of eThekwini consists of rural, peri-urban and urban areas (Jagnath, 2010). A layout of the municipality is presented in Figure 2-15.

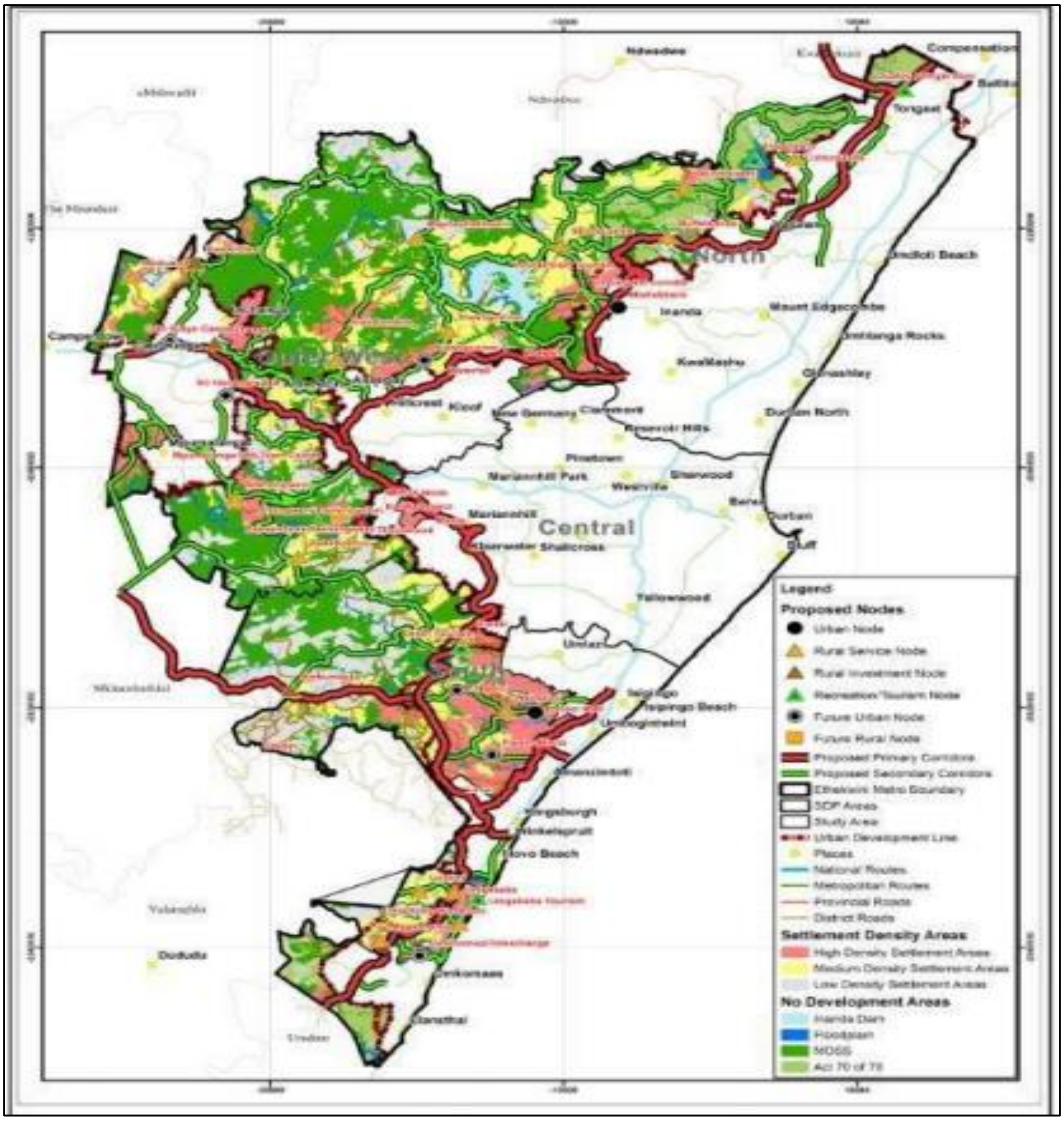


Figure 2-15: Spatial layout of eThekwini according to the 2020 IDP (eThekwini Municipality, 2020)

**Representations for the legend are as follows: Black dots - urban nodes; orange triangles - rural service nodes; brown triangles - rural investment nodes; pink shading – high-density settlement areas; yellow shading - medium density settlement areas and grey shading - low-density settlement areas.*

The IDP states that over 1 million tons of waste were accepted annually by the four main landfills in eThekwini. Waste Services in the eThekwini municipality are conducted by Durban Solid Waste (DSW), with four operational landfill sites: Bisasar Road, Buffelsdraai, Mariannhill and Lovu (Bosch Munitech, 2016). All landfills are equipped with a weighbridge to measure waste entering the landfill. The Lovu landfill was commissioned in 2014, and the Bisasar Road landfill closed in 2016, resulting in three main landfills, Buffelsdraai, Mariannhill and Lovu (eThekwini Municipality, 2020). Two landfills generate electricity, namely Bisassar Road (6MW) and Mariannhill (1MW).

DSW is responsible for weekly household waste collection services (Bosch Munitech, 2016). Waste is collected weekly by a DSW vehicle at the curbside for formal residential areas, where waste is placed into black bin bags by households and onto the curb. Some sites are equipped with orange and clear bags for particular recyclable materials for collection by private waste collectors for delivery at recycling facilities (Bosch Munitech, 2016). The DSW domestic refuse removal user charge from all premises is based on the property value as shown in Table 2-8.

Table 2-8: Monthly domestic refuse removal user charge in eThekwini for 2020-2021 (eThekwini Municipality, 2021)

Property Value	Tariff including VAT (2020/2021)
<= R250 000	exempt
R250 000 – R425 000	41.82
R425 000 – R547 000	72.02
R547 000 – R669 000	92.95
R669 000 – R973 000	123.13
R973 000 – R1 338 000	164.95
>R1 338 000	204.46

The eThekwini Integrated Waste Management Plan 2016-2022 is the latest update to waste statistics in the city (Bosch Munitech, 2016). However, waste generation rates were determined based on average income statistics, population growth and waste generation rates per income level at that time (Bosch Munitech, 2016). According to Bosch Munitech (2016), the most recent Waste Stream Analysis was performed in 1998, with brief updates, citing that measured waste generation rates were outdated. However, waste generation and compositions for the four landfills will be discussed in this section.

There are multiple transfer stations within the municipality for storage before landfills. The Electron Road Transfer Station is the largest and most modern in the municipality. There are 14 garden refuse transfer centres around the municipality that accept household garden waste and other household waste to avoid improper disposal. The DSW has established several buyback centres across the municipality that collect recyclables from public recyclers who want to earn an income. Paper, cardboard, and plastics are recycled through the curbside collection of orange bags.

The combined waste measured at the four eThekwini landfills was 1 272 451 tpa in 2015, with a population of 3 555 868 people (Bosch Munitech, 2016). These are the latest measured quantities; they will be used for further calculations. Since limited information is provided by the IWMP 2016-2022, data was further sourced from Jagnath (2010), who investigated the eThekwini Mariannhill landfill.

Despite the adjustments and estimations made, Jagnath (2010) stated that eThekwini data was still limited in detail compared to later studies in other areas. These average waste quantities were calculated for the Mariannhill landfill for residential and commercial wastes in 2009-2010, further presented in Table 2-9 (Jagnath, 2010). The total amount of waste for Mariannhill was 122 514 tpa in this study, much less than the amount reported in the IWMP of 2016. A comparison between the data by Jagnath (2010) to the waste profile reported by the IDP notes that recyclable fractions were reported as zero in 2015 (IDP), which shows a drastic increase in recycling over the years, possibly attributed to the presence of a material recycling facility reported by the IDP. Nevertheless, waste composition data sourced by Jagnath (2010) was used in this study since it covers a more extensive list of waste sources. However, it must be noted that this waste profile needs to be updated to assess feasibility accurately.

Table 2-9: Waste generation for Mariannhill landfill (Jagnath, 2010)

Waste category	Waste (tpa)	Percentage (%)
Paper and Cardboard	19 856	16.2
LDPE	7 147	5.8
HDPE	2 839	2.3
PET	1 815	1.5
PP	2 542	2.1
PVC	1 089	0.9
PS	2 593	2.1
Glass	10 020	8.2
Metal (Tin/aluminium)	5 966	4.9
Biogenic Waste	49 153	40.1
Other	10 800	8.8
Garden refuse	8 694	7.1
Total	122 514	100

2.5.Waste Management Technologies

Waste management treatment practices should encompass financial sustainability, technical feasibility, environmental sustainability, and social and legal acceptance (Abdel-Shafy & Mansour, 2018). MSW has the economic potential to create revenue, but it strongly depends on the waste management strategy chosen (Simoes & Marques, 2012). It is imperative to have proper characterisation and quantification of sustainable solid waste management systems to inform sound decisions on treatment options.

2.5.1. Engineered Composting

General composting has been practiced for thousands of years, with people discarding organic wastes in heaps or gardens to decompose over time and enrich soils with nutrients. There is a clear distinction between the 'engineered' composting assessed in this study and this basic agricultural type of composting. In engineered composting, mechanical methods promote composting to saleable products. This study focuses on engineered composting, which will be referred to as 'composting' in this dissertation. This will be further discussed below.

The biological treatment, either aerobic or anaerobic, involving microorganisms to decompose biodegradable waste components to obtain energy, CO_2, water and material is called composting (The United States Department of Agriculture, 2000; Dsouza et al., 2021). The decomposition process requires certain environmental and nutritional conditions for the organisms responsible for the process, such that adequate amounts of oxygen, water and nutrients are essential (The United States Department of Agriculture, 2000). Furthermore, the physicochemical properties and environmental conditions such as pH, Carbon/Nitrogen ratio, moisture content, oxygen and temperatures are essential for optimal organism growth (Dsouza, et al., 2021).

Composting is a mature technology with a high TRL and is widely considered an environmentally friendly organic waste management practice (Chen et al., 2020; Barrena et al., 2004). In Africa, composting was one of the first Clean Development Mechanism projects (CDM) implemented (Couth and Trois, 2012). Solid organic waste such as food, kitchen, garden and animal wastes mainly contains organic biodegradables with a high moisture content (85-90%) (Chen et al., 2020). In rural areas, composting is traditionally used to treat food and garden wastes in smaller units (Das et al., 2019). Due to space and odour concerns, in-vessel composting is preferred in urban areas. In-vessel composting, input material can decompose within a container or vessel with forced aeration.

During industrial composting, the degradation of the material is conducted under controlled conditions, allowing the development of favourable temperature for thermophilic bacteria (>45°C) through heating (Couth and Trois, 2012; Chen et al., 2020). Composting occurs in two stages: (1) active composting and (2) maturation or curing. During the active period (bio-oxidation/ thermophilic phase or rotting), microbial activity breaks down fast degrading material and slow decaying material such as cellulose. The curing period follows where lower levels of microbial activity decompose products of the active stage into humus (carbon-rich brown substance). Finally, once curing is completed, the compost is referred to as stable and used as a product. The overall composting process is according to Figure 2-16 and Equation 2-1.

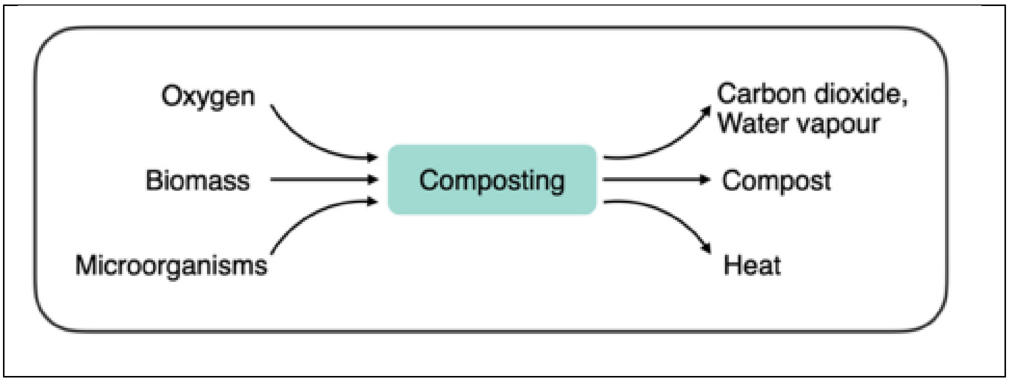


Figure 2-16: General composting process representing inputs and output as biomass decomposes

Equation 2-1

$$(C_6H_{10}O_4)_x + 6.5O_2 \rightarrow (C_6H_{10}O_4)_{x-1} + 5H_2O + 6CO_2$$

A vital step in composting is the size reduction of particles to improve the homogeneity of biogenic material, which a shredder can achieve. The advantages of size reduction include increasing reaction rates by enabling a greater surface area, allowing microorganisms to digest material more efficiently, and increasing overall process efficiency. Furthermore, the mixing and turning of material promote aeration, uniform and even distribution of microorganisms, nutrients and moisture. Aeration also reduces odour through the periodic turning of waste.

Composting is also possible through earthworms, referred to as vermicomposting. This method has gained popularity due to the fast decomposition of waste materials. A summary of different composting technologies is given in the National Composting Norms and Standards (DEA, 2013). In Cape Town, approximately 30% of green waste is composted. Composting organic waste converts 3.1 Mt of waste annually and reduces GHGs by about 20% in South Africa (Oelofse, 2019).

Compost, the product of composting, is a stable organic material high in humus - used as organic fertilisers or to replace mineral fertilisers or soil conditioners (Couth & Trois, 2012). The addition of humus to soil retains water and nutrients, lessens the bulk density of the soil, and increases spaces for aeration to occur. From an environmental standpoint composting reduces the collection and transportation of biodegradable waste (Barrena, et al., 2014). However, GHGs (carbon dioxide) and unpleasant odours (hydrogen sulphide) are generated at times through composting, and if not properly managed, the presence of heavy metals in municipal organics decreases compost quality (Barrena et al.,2014). The production of GHGs through composting can be considered much less harmful than methane at landfill sites (Couth & Trois, 2012). In industrial MSW, the different composting techniques are turned windrow approaches (suited to large scale), open aerated systems, and contained systems (reactors and agitated systems).

There have been high failure rates for municipal composting in developing countries due to high transportation, management and operational costs, improper sorting and lack of process knowledge, while residential (small scale) composting works well (Viljoen et al., 2021). In rural communities, households often repurpose organic wastes like wood, dung, sawdust, crop residues, paper, and cardboard as heating sources. Other wastes such as kitchen scraps, meat and bones are used as animal feed (Viljoen et al., 2021).

Economics of composting process

Dome Aeration Technology (DAT) composting costs in South Africa have been extensively studied. The DAT technology (Figure 2-17) is designed on a self-aeration principle that can distribute oxygen throughout the compost heap (Moodley, 2010). Microbial activity increases the temperature to around 40–60 ℃ (Couth & Trois, 2012). Domes and channels are created using steel mesh structures allowing air to move through the windrow, controlling oxygen and temperature. According to Moodley (2010), the DAT is appropriate for South Africa due to low capital costs, low energy inputs, limited plant requirements, and labour-intensive operations. Furthermore, Couth and Trois (2012) also stated that the DAT was selected for the first Mechanical Biological Treatment (MBT) process in South Africa due to the low cost zero/low energy characteristics.

Equipment such as front-end loaders and excavators can be used to prepare and place input material into windrows, whilst the initial stages of domes and channel placement can be done by local labour. About eight labourers are required for a 110 tpd waste composting facility: six sorters and two supplementary feed workers (supplying the chippers). After the composting time, which is typical 16 weeks, the product is put through a drum screen to sieve out material that has not composted and deposited into a stockpile where it is taken for bagging and bulking (Moodley, 2006). The general DAT process at the Bisesar landfill in Durban was explained by Couth and Trois (2012). The waste material received by ROTOPRESS trucks were preferred due to the mixed and shredded material at the Bisasar landfill. The MSW waste delivered by these trucks were mixed with woody waste (structural material) using Articulated Dump Truck (ADT) and loaded onto a truck by an excavator. Upon the placement of material on-site further mixing and wetting occurred. The composting process was 16-20 weeks at a maximum, with sampling every eight weeks.

The capital cost of a composting unit in eThekwini was R2 400 000 to process 180 tpd for the study in 2007 (Reddy, 2016). The yield of compost, estimated by a degradation factor (75% according to Reddy (2016)), is sold for income. This implies that about 75% of organic waste is degraded into commercial compost. The operating costs (miscellaneous materials, labour, a front-end loader, water and packaging) were approximately R150/ton. Sufficient income from composting sales is required to offset the capital and operating costs of the process.

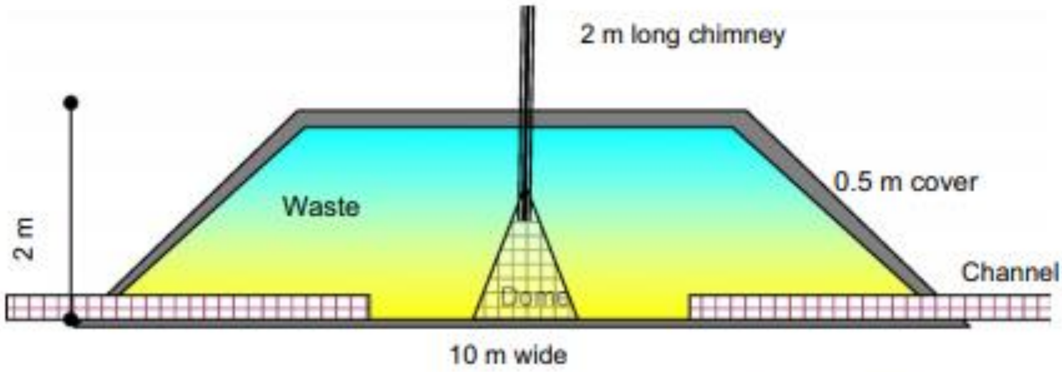


Fig. 1. Schematic cross-section of a typical DAT windrow (Trois et al., 2007).

Figure 2-17: Diagrammatic representative of a DAT windrow (Reddy, 2016).

2.5.2. Anaerobic Digestion

Anaerobic digestion (AD) biologically converts organic components of MSW microbially in the absence of oxygen, producing a methane and carbon dioxide-rich gas named biogas (Gogela, et al., 2017). The AD process occurs in a gas sealed reactor known as an anaerobic digester to provide an enabling environment for microorganisms to convert organic matter into biogas and digestate (Mutz, et al., 2017). Biogas is typically used to create energy (heat and electricity) and, in the future, could be used to fuel motor vehicles. The digestate is nutrient-rich and also can be used as a fertiliser.

AD is suitable for biodegradable organic matter with low contents of fibrous material such as hemicellulose and lignin, which degrade at a slow rate (Mutz, et al., 2017). This wide range of feeds (excluding wood) is typically used to provide waste management solutions (AEBIOM European Biomass Association, 2008). Organic waste separated from MSW from households, markets, and garden waste is also suitable for AD. Co-digestion of agricultural and sludge from wastewater treatment is more complex and not considered further in this dissertation.

The AD feedstock requires pre-treatment to homogenise feed (separating non-digestible materials and shredding) before waste digestion occurs (Purser, 2011). The product gas is recovered, and the residue is sent for treatment. The waste received by AD is usually source-separated to remove non-desirable materials in the feed, such as glass or metals. After that, the waste is shredded before being fed into the digester. Once in the digester, the feed is diluted to attain the desired solids content and remains in the digester for a pre-specified retention time. The organics are digested, typically within 35 days, and forms biogas. When AD is complete, and the digesters are emptied, it is crucial to leave approximately 10 – 15% behind in the reactor, as this will act as an inoculum for the next batch (Purser, 2011).

Anaerobic digestion involves four main biochemical processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These processes for converting organic substrates (such as proteins, carbohydrates, and lipids) into biogas are described in Table 2-10.

Table 2-10: Examples of conversion of selected compounds during anaerobic digestion (El Mashad and Zhang, 2020)

Sub-processes	**Examples of Equations**
Hydrolysis	Conversion of carbohydrates and proteins: *Equation 2-2:* $\mathrm{Cellulose} + \mathrm{H_2O} \rightarrow \mathrm{sugars}$ *Equation 2-3:* $\mathrm{Proteins} + \mathrm{H_2O} \rightarrow \mathrm{amino\ acids}$
Acidogenesis	Conversion of glucose into acetic and propionic acids: *Equation 2-4:* $\mathrm{C_6H_{12}O_6} \rightarrow \mathrm{3CH_3COOH}$ *Equation 2-5:* $\mathrm{C_6H_{12}O_6} + \mathrm{2H_2} \rightarrow \mathrm{2CH_3CH_2COOH} + \mathrm{2H_2O}$
Acetogenesis	Conversion of propionate and butyrate into acetate and hydrogen as follows: *Equation 2-6:* $\mathrm{CH_3H_2COO^-} + \mathrm{3H_2O} \rightarrow \mathrm{CH_3COO^-} + \mathrm{HCO_3}^- + \mathrm{H^+} + \mathrm{3H_2}$ *Equation 2-7:* $\mathrm{CH_3CH_2CH_2COO^-} + \mathrm{2H_2O} \rightarrow \mathrm{2CH_3COO^-} + \mathrm{H^+} + \mathrm{2H_2}$ *Equation 2-8:* $\mathrm{4H_2} + \mathrm{2HCO_3}^- + \mathrm{H^+} \rightarrow \mathrm{CH_3COO^-} + \mathrm{4H_2O}$
Methanogenesis	Conversion of acetic acid, carbon dioxide and hydrogen, and methanol to methane: *Equation 2-9:* $\mathrm{4CH_3COOH} \rightarrow \mathrm{4CO_2} + \mathrm{4CH_4}$ *Equation 2-10:* $\mathrm{CO_2} + \mathrm{4H_2} \rightarrow \mathrm{CH_4} + \mathrm{2H_2O}$

	Equation 2-11: $4CH_3OH + 6H_2 \rightarrow 3CH_4 + 2H_2O$

The AD product can be used for direct combustion and electricity production methods. The biogas conversion efficiencies using different technologies are presented in Table 2-11. Combined heat and power (CHP) technologies offer much greater total efficiencies when compared to micro gas turbines, fuel cells and engines. Furthermore, CHP is preferred and commonly used since it can be used for electrical and heat production (Gogela, et al., 2017). Biogas may be stored at the production site, compressed and bottled for sale. Upgrading biogas is required for transportation which can be costly (Gogela, et al., 2017).

A comparison of AD to composting shows that the methane produced during AD can be used as an energy source, however, a more homogenous feedstock is required increasing capital investments, and some technical expertise is needed to operate and maintain facilities (Couth & Trois, 2012). AD is less favourable to composting in Africa (Couth & Trois, 2012). Biogas can typically replace fossil fuels such as firewood used in rural households as the primary energy source. Additionally, the GHGs produced from biogas is much lower than fossil fuels, decreasing overall emissions.

Table 2-11: Conversion efficiencies of different biogas technologies (Gogela et al., 2017)

Technology	Electrical efficiency (%)	Thermal efficiency (%)	Total efficiency (%)
Combined heat and power (CHP)	33 – 45	35 – 56	~85
Micro gas turbines	26 – 33	None	26 – 33
Fuel cells	40 – 55		40 – 55
Engines (Pilot Injection, Gas-Otto)	30 – 44		30 – 44

There are about 500 biogas digesters in South Africa, mainly rural digesters for cooking fuel and commercial digesters ranging from small to 19 MW electricity production plants (Gogela et al., 2017; Osei-Appiah and Dioha, 2019). Furthermore, Gogela et al. (2016) found that the biogas investment potential in the Western Cape was R4 billion, with a possible 320 to 3 950 direct job potential (the job intensity was proposed as 4 to 10 jobs per a megawatt of installed electrical capacity).

Economics of AD

The capital costs of AD varies based on plant capacities and input feed. Generally, there is a lack of data based on capital and operating costs of AD processes, especially in South Africa. However, the capital costs of AD digesters have been studied to a greater extent in European countries. Mutz et al. (2017) provided examples of anaerobic digestion of sorted MSW capacities between 50 000 and 150 000 tons of waste input per year. The data was adjusted for developing countries (lower salary costs). The initial investment was estimated between 1 to 20 million EUR, with capital costs ranging between 12 and 19 EUR per ton of waste inputted (Mutz, et al., 2017).

Furthermore, a detailed analysis was conducted by Rapport et al. (2015) based on two previous feasibility studies on AD facilities conducted by authors Tsilemou (2006) and Clarke (2000). The capital and operational costs, including predevelopment, construction, labour maintenance etc., were considered in the cost curves produced (Rapport, et al., 2015). Although these studies were conducted ten years apart (Tsilemou et al., 2006 and Clarke, 2000), they exhibited similar trends. The scaling factor (n – which is further discussed in chapter 2.6) for both studies was approximately 0.5. The capital cost curves reproduced by Rapport et al. is provided in Figure 2-18. These curves are widely used to estimate costs related to AD facilities. The equation developed by Tsilemou et al. (2006), due to R^2 value closer to one, was used for further calculations conducted in 2006 (Rapport et al., 2015).

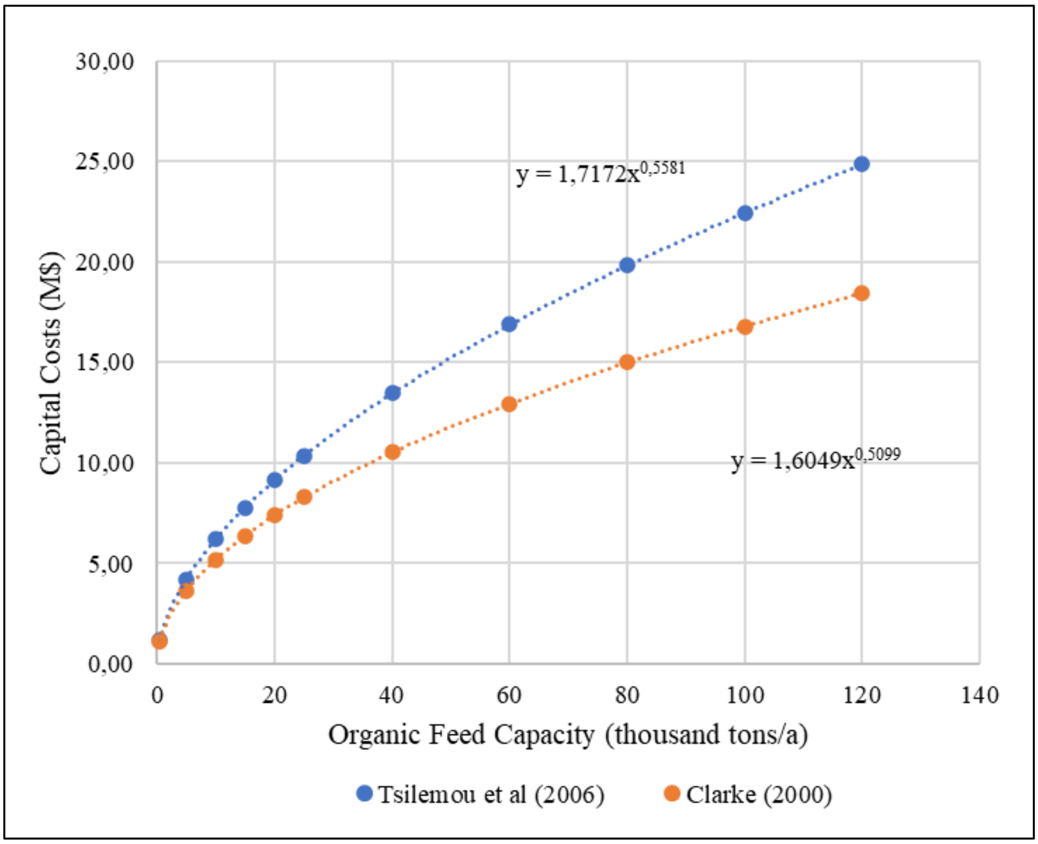


Figure 2-18: Capital cost curves for European MSW digesters for 2007 in dollars (adapted from Rapport et al. 2015)

Furthermore, Ullah (2015) calculated the total number of jobs at 19 for a 100 000 tpa AD facility, namely, one project manager, one marketing manager, three process control operators, two tip floor operators, two maintenance technicians, one lab technician, two-scale house operators, one receptionist and six general labourers.

A Biomass Road Map for Europe was created by AEBIOM (European Biomass Association) that examined the status of biomass projects within the sector. The study found that a 500 kWe biogas plant on a farm, including a CHP unit, costs about €2 million in Germany, with the specific cost per kW of electricity decreasing as the plant size increases (AEBIOM European Biomass Association, 2008). The road map further reported the costs of small scale units for different sizes in Germany and Italy, as represented in Table 2-12. On the other hand, a €1 million Nm^3/a biomethane unit investment ranged between €3.4 million for a standalone plant and €3.9 to 4.9 million for gas grid-connected plants (based on the length of the gas grid and upgrading or biomethane filling stations).

Table 2-12: Investment costs of biogas units based on kWe in Germany and Italy (AEBIOM European Biomass Association, 2008).

Location	**Germany**		**Italy**	
	kWe	**€/kWe**	**kWe**	**€/kWe**
CHP (gas engine)	150	900		
CHP (gas engine)	250	740		
CHP (gas engine)	500	560		
Biogas Plant	Up to 100	5 000 to 3 000	200	4 900
Biogas Plant	100 to 350	3 000 to 2 500	500	3 800
Biogas Plant	Above 350	<2 500	1000	3 200

Gogela et al. (2017) conducted case studies on biogas processes in the Western Cape to assist those considering installing biogas facilities. At the time of reporting, there were 21 biogas projects in the Western Cape. The costs associated with biogas facilities in South Africa, the digestor with CHP and peripheral equipment were the highest for the process. A cost curve for CAPEX was generated based on the electricity generated in South Africa, with the average operational cost found as R253 per hour per kWe (based on South African and German literature data). The study found that small scale commercial biogas facilities (< 50kWe) were not feasible due to the current (low) landfill disposal and energy costs. According to Gogela et al. (2017), the input assumptions for a small scale AD plant of 1.3 tons a day of food waste is assumed to produce 176 MWh/a of electricity and 251 MWh/a of heat with a power output of 25 kW. The capital cost of such a facility in the Western Cape was R5.9 Mio in 2011. The power purchase price was considered as R1.10/kWh.

2.5.3. Thermal Treatment - Pyrolysis

The framework and conditions for waste to energy (WTE) projects in developing countries are vastly different from those successful in Europe, North America, Japan and China. There have been few projects in developing and emerging countries with successful long term operations (Mutz et al., 2017). Generally, developing countries have low calorific value in MSW, little waste separation, weak business models, and a lack of knowledge on WTE plants (Mutz et al., 2017).

Theoretically, incineration is also considered a WTE technology. Globally, with over 2000 waste incineration plants are operational, with most in Japan (1200 installations) and Europe (500 installations) (Kepys and Jaszczura, 2020). However, this study purposely did not consider incineration since it is a specialised technology requiring high capital investments and specialised skills and is environmentally less favourable. Furthermore, pyrolysis and gasification have been considered better options than incineration regarding technical, environmental and financial parameters. In South Africa, there has been the introduction of small-scale pyrolysis and portable gasification units that could be transported to locations (Whyte, et al., 2020). Pyrolysis can treat specific waste fractions such as plastics within one unit, limiting the number of specialised workers and costs that are usually associated with incineration and gasification practices.

The thermal degradation of a material in the absence of auxiliary oxygen is called pyrolysis. Due to the absence of oxygen, pyrolysis is deemed more environmentally friendly since fewer pollutants are created than processes conducted in the presence of oxygen (combustion). In general, thermal degradation of organic molecules occurs in the initial stages of the process at temperatures between 500 and 800 ℃ (Mutz, et al., 2017). The three products are typically produced: combustible gases (viz. methane, hydrogen, hydrocarbons, and carbon monoxide), liquids, and solid residues (char).

Historically, there have been no successful experiences with high volume MSW treatment facilities due to the heterogeneity of mixed waste. More recently, pyrolysis plants are being tested to degrade carbon rich organic materials such as MSW. However, to the best of the author’s knowledge, no pyrolysis MSW plants have been reported in South Africa, except for the literature on pyrolysis of waste tyres. A waste tyre pyrolysis plant business model was developed by Nkosi et al. (2020) in Gauteng to evaluate the feasibility of the operation. According to PlasticsSA (2020), there are presently no commercial WTE facilities in South Africa; but sometimes tyre pyrolysis plants burn plastics to reduce sulphur levels, and some informal home-built units are used to burn waste. Still, these are not suitable for recycling and using derived fuels for their purposes (Plastics SA, 2020). Although there is no official data available, PlasticsSA (2020) assumed a plastics recovery rate (1 200 tpa) allocated to WTE operations consisting of formal, informal trail processes in 2019 (Plastics SA, 2020).

Plastics are produced from petrochemicals that have a high caloric value. The conversion of waste plastic to oil is possible. The high molecular weight of waste plastic molecules can be thermally cracked at high temperatures, resulting in lower molecular weight molecules that are liquid or gaseous under ambient conditions. The relative proportions of products depend on the pyrolysis method, reaction parameters, and feedstock quality. Although it can potentially reduce the amount of plastic waste found in landfills and littered, pyrolysis of plastic is sensitive to the collection of adequate plastics, the quality of the plastic collected and the uptake of pyrolysis fuel on the market.

The Hooker Chemicals and Plastics Corp started construction for a 2 500 tpd waste to energy system to supply steam for a company in Niagara Falls as early as the 1980s. Furthermore, in Niagara Falls, New York, a plant collected waste plastic (PE, PP and PS with some PET and PVC) for a two-part treatment, namely, 1. the pre-treatment and 2. liquefaction of waste plastics. All PET bottles, metal and foreign materials like glass and sand were removed and sent to the landfill. The ground plastics were dehydrochlorinated and then forwarded to the pyrolysis tanks at 420 °C (Lin, 2018). This process converted 100 kg of waste plastics into oil, gases and residues (Lin, 2018). A similar facility in Sapporo, Japan, was constructed in 2000. The plant processes 14 800 tons of household waste plastics (PE, PP, PS, and PVC). The government collected the plastics and supplied them to the Sapporo Plastic Recycling Plant. Like the Niagara plant, pre-treatment to shred plastics was required (Lin, 2018). The shredded plastic was further dried and pelletised before being fed dehydrochlorination. The Kingtiger Group, a waste processing company in China, offers multiple waste-to-oil plants (Lin, 2018): a batch process can process ten tpd plastic waste, a semi-continuous 20 tpd, and a continuous system possesses 30 tpd capacity. For plastic waste, pre-treatment is required, where collected waste plastics must be dried and shredded into smaller pieces. A simple material balance assumes that 100 tons of waste plastics produce about 45 tons of pyrolysis oil and 40 tons of carbon black, and 15 tons of gases (Lin, 2018). Another process by Niutech found that 100 tons of waste plastic produce 45 tons of oil and 34 tons of carbon black (Lin, 2018).

PlasticsSA (2020) reported that pyrolysis is best suited for plastic mixtures of polyethylene and polypropylene. One of the largest projects of naphtha to plastics is by Brightmark Energy, with who Dow is considering a partnership with Dutch start-up Fuel. This project plans to provide naphtha like oil from the Fuenix pyrolysis process to the Dow petrochemical plant in the Netherlands to produce

100% grade food-approved plastic from plastic waste. Research conducted by the Dutch Think Tank further estimated that the avoidance of production of virgin materials, and depolymerisation saves 1.5 tons of CO_2 per metric ton of plastic recycled. In comparison, mechanical recycling saves 2.3 tons of CO_2 per metric ton recycled (Plastics SA, 2020). However, these processes are chemical and mechanical, therefore processing different grades of plastics and resulting in different carbon footprints.

Ideally, recovery of monomers rather than fuel recovery is preferred, however, it is inherently more challenging to achieve (Pandey et al., 2020). According to Pandey et al. (2020), Hydrocarbon rich liquid (C11-C-20) is achievable through catalytic fast pyrolysis, resulting in diesel-like properties. The thermal cracking of plastics occurs between the temperatures of 450 – 650 °C, based on the type of plastics, and the reaction temperature strongly influences the product yields (Fivga & Dimitriou, 2018). However, the addition of catalyst enhances the degradation of the plastic at lower temperatures (230–350°C) (Pandey et al., 2020). At lower temperatures of 230–450°C, the product is mainly liquid with only small amounts of gas components. At higher temperatures (450–700°C), a considerable amount of gas is produced together with the pyrolytic liquid (Pandey et al., 2020). Furthermore, adding catalysts such as zeolites promotes the process and improves aromatic liquid yield, as per the process used by Fivga and Dimitriou et al. (2018). The composition of components in the pyrolytic liquid varies with the catalyst as a specific catalyst has higher selectivity for a specific range of hydrocarbons.

The yield of the pyrolytic liquid varies significantly with the feed used in the process. Generally, PP as feed produces the highest liquid yield (up to 80%) (Pandey et al., 2020). Similarly, the pyrolysis process investigated by Fivga and Dimitriou et al. (2018) is designed with an 85.8% yield. The liquid obtained from thermal pyrolysis of PP has the highest liquid content with a distillation temperature of <170°C. However, the heating value of the pyrolytic liquid for all kinds of polyolefin pyrolysis is 44–46 MJ/kg, which is about the same as diesel or gasoline. Thus, the pyrolytic liquid is suitable for use as a liquid fuel. It can be concluded that the liquid fuel produced in both thermal and catalytic pyrolysis is a function of reaction time, temperature, and feedstock. The liquid fuel obtained in thermal and catalytic pyrolysis can be used for various applications if it is purified using fractional distillation.

The chemical reaction that usually occurs in the pyrolytic chamber of reactors:

Equation 2-12:

$$\mathrm{C_nH_mO_p}\ (\text{biomass or polymer}) \xrightarrow{\text{heat}} \sum_{\text{liquid}} \mathrm{C_x\,H_yO_z} + \sum_{\text{gas}} \mathrm{C_aH_bO_c} \ +\ \mathrm{H_2O} + \mathrm{C}\ (\text{char})$$

Economics of pyrolysis

According to Riedewald et al. (2020), the economic performance of mixed waste plastic pyrolysis has been assessed in just a few pyrolysis plants, resulting in an overall lack of reliable data making comparison and evaluation challenging (Riedewald et al., 2020). The economic costs of MPW plants from different literature sources were investigated by Riedewald et al. (2020) and presented in Table 2-13. These sources are primarily comprised of simulated processes.

Table 2-13: MPW waste plants from literature (Riedewald, et al., 2020)

Location	**Malaysia**	**UK**	**Not specified**	**Belgium**
Reference	Sahu et al., 2014	Fivga and Dimitriou, 2018	Jiang et al., 2020	Riedewald et al., 2020
Type of literature	ASPEN simulation	ASPEN simulation	ASPEN simulatio	ASPEN simulation
Comments	Catalytic fluidised bed reactor required throughput of > 120 000 tpa to be economically viable	Fluidised bed reactor with three different throughputs (1 000, 10 000, and 100,000 kg/h).	Molten salt MPW pyrolysis plant – 16 000 tpa plant throughput	Molten salt MPW pyrolysis - 42 000 tpa of MPW throughput
Capital cost	$58 Mio	₤1 Mio for a 100 kg/h facility to ₤56.7 Mio (for 100 000 kg/h plant)		€20 190 000

The process studied by Fivga and Dimitriou (2018) will be further discussed. The process occurs in a fluidised bed reactor due to high heat transfer and low vapour residence time, resulting in higher liquid/wax yields in an inert atmosphere at a fixed reaction temperature and atmospheric pressure. The process was developed by a recycling company based in the UK, consisting of four functional units: pyrolysis of plastic waste, char separation, collection of pyrolysis fuel oil, and combustion of the by-product

Fivga and Dimitriou (2018) investigated the process and considered a reactor temperature of 530 ℃ to increase liquid/wax yields. Products exiting the reactor were maintained at 530 °C. The vapours are sent to a solid separation unit to separate char (using a hot ceramic vapour filter unit (HVF)) and sent to a combustion unit. The required fluid velocity is maintained by partially recycling pyrolysis vapours back to the reactor, limiting the need for additional nitrogen and increasing energy efficiency. Nitrogen is required during start-up processes. Furthermore, the recycled pyrolysis vapours cover the heat requirements of the unit partially.

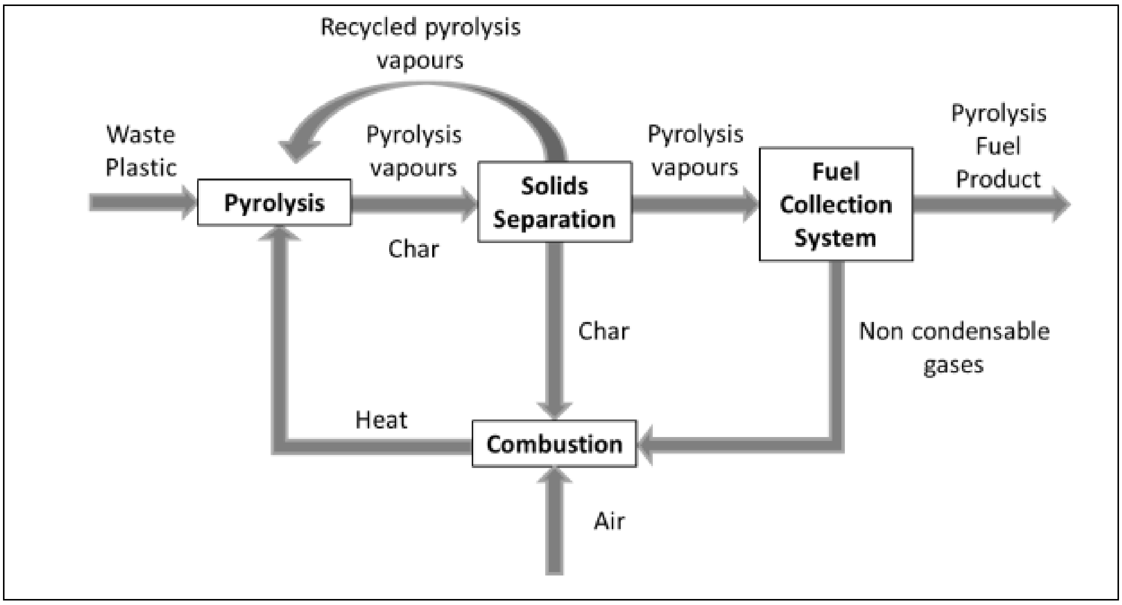


Figure 2-19: Diagram of the pyrolysis process for fuel production (Fivga and Dimitriou, 2018)

The non-recyclable vapours are sent to a series of heat exchangers and separators for condensation and storage. Following the heat exchanger series, the exit temperatures were 400 ℃, 200 ℃, 80 ℃ and 25 ℃ (Fivga & Dimitriou, 2018). Water is provided in a closed look at 40 ℃ to the first heat exchanger and 10℃ to the last exchanger. The condensed fuel exiting each separator is sent to a closed tank (storage). The process diagram is presented in Figure 2-19. The mass flow rate of each condensed fuel stream is continuously monitored for adjustments to operating parameters in case the flow rate varies from the design specifications due to feedstock variations. This is necessary since waste compositions vary. A fuel tank is a buffer to balance these fluctuations and ensure fuel homogeneity. The remaining non-condensable gases and the separated char are recirculated to a secondary fluidised bed reactor, where they are combusted to generate the thermal energy required by the pyrolysis reactor.

The process was modelled using Aspen HYSYS using the Peng-Robinsons thermodynamic property method. The feed mixture of PE, PP, and PS assumed 85 wt.% carbon and 15 wt. % hydrogen on a dry ash-free basis (Fivga & Dimitriou, 2018). The numerous exothermic and endothermic reactions within the pyrolysis fluidised bed reactor make the calculation of data on heat transfer very complicated. This study assumed that 1 kg of waste plastic (dry) required 1 316.1 kJ/kg of thermal energy for the pyrolysis process (Fivga & Dimitriou, 2018). The 100kg/h plant's major energy input was 1 224 kW (Lower heating Value - LHVdry) with a production of 85.8 kg/h of fuel (1055 kW). The mass yield was 85.8%, in agreement with the literature. The fuel energy efficiency was determined by dividing the energy in the pyrolysis fuel output by the energy content of the plastic waste. The fraction of the energy retained in the product was 86% (LHVdry). Pyrolysis is an endothermic reaction requiring a constant source of energy. In the examined pyrolysis process, this thermal energy is provided by combusting the pyrolysis by-products (i.e. char, non-condensable gases). The available thermal energy from burning char and the non-condensable gases calculated by Aspen HYSYS is 156.7 kWt. As discussed in Section 3.1 the total thermal energy for the pyrolysis reactor is approximately 41.16 kWt; therefore, an external heating source is not required.

The higher heating value (HHV) of the feedstock was calculated using the following formula (Fivga & Dimitriou, 2018):

Equation 2-13:

$$\mathrm{HHV_{dry}}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) = 0.3491\mathrm{C} + 1.1783\mathrm{H} + 0.1005\mathrm{S} - 0.1034\mathrm{O} - 0.015\mathrm{N} - 0.0211\mathrm{A}$$

Where, C, H, S, O, N and A represent mass percentages on a dry basis of feedstock carbon, hydrogen, sulphur, oxygen, nitrogen and ash contents.

The feedstock's lower heating value (LHV) is calculated using (Fivga & Dimitriou, 2018).:

Equation 2-14:

$$\mathrm{LHV_{dry}}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) = \mathrm{HHV_{dry}} - 2.442 \times 8.936\frac{\mathrm{H}}{100}$$

The HHV of dry plastic waste used in this study is calculated using Equation 2-13 and amounts to 47.35 MJ/kg, while the LHV is calculated using Equation 2-14 and amounts to 44.07 MJ/kg (Fivga & Dimitriou, 2018).

According to the process above, the mixed plastic pyrolysis unit modelled by ASPEN was economically evaluated in the United Kingdom (UK) in 2013. The equipment cost included the pyrolysis reactor, vapour filter, combustor, and labour. The plant life was considered 20 years (Fivga & Dimitriou, 2018), which lies between the usual plant life of 20-25 years of thermal plants. The reference total capital cost of the pyrolysis WTE plant was estimated at ₤1 Mio for 100 kg/h of the plastic waste facility, as seen in Table 2-13 (Fivga & Dimitriou, 2018). Furthermore, the raw material cost was assumed zero. The operating cost was ₤416 325/a, utilities cost ₤14.685/a, and total product sales was ₤330 896/a (Fivga & Dimitriou, 2018). The fuel production cost was estimated at ₤19.30/ GJ or ₤0.87/kg (Fivga & Dimitriou, 2018). The sale cost of pyrolysis fuel was ₤0.55/kg, and electricity was priced at₤ 0.0586/kWh (Fivga & Dimitriou, 2018).

Effectively, this process required much less refining and lower overall production costs (than road transport fuels), making this plastic waste pyrolysis method potentially more attractive for investors. The small process (rural) scale significantly influences the economics of the pyrolysis process as the lower operating labour costs will reduce the total production costs. The plant operated for 24 hours for 293 days annually, with ten operators required to run the facility (Fivga & Dimitriou, 2018).

2.5.4. Recycling

As discussed in section 2.1.5., recycling is not largely practised in South Africa. The NEM: WA describes the recycling process reclamation of waste for further use, including separation and processing of recycled material (DEA, 2016). The recycling manual published by the DEA (2016) further lists the following recycling activities: the collection of waste material that can be repossessed, the separation of waste material at a Material Recovery Facility or transfer station, delivery to recycling plants, processing of waste material by shredding, grinding, rinsing and melting or using reprocessed materials for manufacturing new products and the selling of new products to consumers.

It usually takes less energy to recycle material than to produce raw materials. For example, recycling scrap aluminium cans can save up to 95% less energy than making cans from bauxite ore (raw material). Although energy saving may not be as high for all recyclable products, it is recurrent through many products (EIA, 2010).

Recycling Sector 2019

According to GreenCape (2020), the South African dry recyclable sector is well supported by industry-driven associations. The active industry associations and stream estimates are presented in appendix C (GreenCape, 2020). According to the data provided by GreenCape (2020), the waste streams diverted from landfills (percentage of collected/diverted waste to material in circulation) are metal cans (102%), cardboard (82%), glass (82%), and streams with a lower diversion percentage are paper (50%), and plastic derivatives (ranging 10% to 49%).

Transport of Recyclables

A significant cost associated with recycling is transportation to BBCs or recycling facilities. There is limited information on the cost of transportation of recyclables, but it can be based on the cost to transport material. Fleetwatch developed a trucking benchmark to determine the factors influencing capital and operational cost associated with trucking (Braun, 2019). The objective was to provide operators and shippers with a reliable, independent guide to trucking costs for different materials (Braun, 2019).

A summary of cost per km was also developed for 2019, with prices ranging depending on the type of haul and load capacity, as presented in Table 2-14 (Braun, 2019). It is to be noted that the fuel price was significantly lower in August 2019 than in 2021 (the highest for the country). Thus this estimate is assumed to be lower than current rates and will be further investigated through a sensitivity analysis. The costs per ton per km for different haul types are presented below in Table 2-13.

Table 2-14: Summary of operating costs for transporting materials from Fleetwatch benchmarks August 2019 (Braun,2019)

Total CPK (Rands/km)	Short-haul Metro (Stop/Start)	Medium Haul (Fresh Del)	Long Haul (Fresh Del)	Medium haul (Cargo Van)	Long Haul (Cargo Van)	Truck Medium Haul (Flat Deck)	Truck and Trailer Long Haul (Flat Deck)
Cost per Ton/km (100% load)	4.50	8.78	3.81	2.45	1.64	1.67	0.77
Cost per Ton/km (75% load)	6.01	11.71	5.08	3.27	2.19	2.22	1.02
Cost per Ton/km (50% load)	9.01	17.57	7.62	4.91	3.28	3.33	1.54

2.5.5. Cost of recyclates

The cost of different recyclates differ throughout the country and is largely based on feed location to BBCs or recycling facilities. A comprehensive study of the cost of different recyclates for 2011 across different BBCs in the country was compiled by Viljoen et al. (2019) (Table 2-14). Table 2-14 shows that the price paid by BBCs for recyclables differs depending on location within the country. These prices will determine the monetary value of specific recyclates based on the closest location.

Table 2-15: Cost of recyclables from BBCs across the country in R/t of recyclable in 2011 (adapted from Viljoen et al., 2019)

Type of recyclable	Bloemfontein	Cape Town	Durban	East London	Johannesburg	Kimberly	Mafikeng	Nelspruit	Pietermaritzburg	Polokwane	Port Elizabeth	Pretoria	Upington
White paper	910	660	1140	350	1260	930	1000	480	1080	500	500	1850	200
Coloured paper	430	400	310	400	500	800	1000	180	680	100	650		200
Magazines and books	180	240	250	230	340	200	200	180	300	100	350	240	200
Newspaper	180	240	250	230	250	200		180	330	100	270	170	200
Mixed Paper	200	280	350	230	250	600	1000	180	230	100	400	130	200
Cardboard	240	280	510	300	500	200	400	280	500	150	280	520	200
PET	1480	780	930		2800	1330	1500	330	1800		700	1170	
HDPE	750	500	730	350	1080	600	500	330	1200		550	770	
PVC	600	5000	700		950	450	500	150	800		600	1600	
LDPE	750	600	1000	500	1200	500	500	330	1200		1200	1380	
PP	830	500	1000		1630		500	150	1200		1500	400	
PS								150				600	
Plastic mix	830	320	700		750	550	500	280				420	
Cans	360	1040	1000	400	580	700	500	180	1000	500	400	430	630
Glass	220	210	180		280	150	330	250		200	230	250	
TetraPak					300		400		1000		400		
Other metal		2000	750		1170		1400		2000		1500		1430

2.6. Techno-Economic Assessment

For analysis of the most suitable technology or combination of technologies, it is important to determine whether the project is economically viable before intense, expensive and time-consuming design and scoping is performed. Techno-economic assessments use an order of magnitude approach as predesign cost estimates which require much less detail than firm estimates. These assessments are vital comparative design tools and allow one to determine whether a proposed project should be considered further (Peters et al., 2003). The technique is based on the cost-benefit principle, which can assess a specific project's economic feasibility, cash flows over the lifetime, evaluate the possibility of different technology scales and applications, and compare results (higher profit margins than competing projects). Techno-economic assessments consider parameters including design process, process modelling, safety features, equipment sizing, capital cost estimation, and operating cost estimation. For this assessment, it is assumed that the technologies investigated are already processed and design fit and model considerations have been finalised. Thus, the critical parameters investigated relate to the capital and operational costs.

Since cost-benefit methods are based on existing plants or literature data, the accuracy of estimates ranges between 30 to 50%, which has been deemed acceptable (Naidoo et al., 2019; Sinnot, 2005). Similarly, these assessments have been increasingly used in the waste field to determine the viability of waste treatment processes.

There are several TEA methods viz.: Static cost-benefit assessment, Annuity method, Net cash flow table, Net present value (NPV) (which considers discounted cash flow), and Internal Rate of Return (IRR) (Peters et al., 2003). A typical techno-economic assessment assesses capital and operational expenditure, and the economic analysis determines favourable conditions, represented by indicators (Sinnot, 2005). These indicators are usually dependent on the technology's technical maturity. The technology maturity, sometimes referred to as technical readiness level (TRL), can indicate data availability and inform if estimation methods can be used or avoided (Zimmerman et al., 2018). Both technical and economic analysis become more reliable with the maturation of the technology.

2.6.1. Order of Magnitude TEA Methodology

For an order-of-magnitude techno-economic assessment (OOM-TEA), five steps are followed: Data collection, estimation of CAPEX and OPEX, economic (discounted cash flow) analysis, and evaluation of the results (sensitivity analysis) (Naidoo et al., 2019). Since OOM-TEAs are a preliminary estimation that allows the comparison of process alternatives with a similar level of detail, extensive mass or energy balances are not required, and literature data and data from existing plants are used.

2.6.2. Capital Expenditure (CAPEX)

The bulk of literature data is delivered to the CAPEX calculations (overall equation presented in Equation 2-9), where localised capital investment is calculated and further used to determine operational costs (Naidoo et al., 2019).

Equation 2-15

$$\mathrm{FCI_{new}} = \mathrm{FCI_{Ref}} \times \left(\frac{\mathrm{Capacity_{new}}}{\mathrm{Capacity_{Ref}}}\right)^{\mathrm{n}} \times \left(\frac{\mathrm{CEPCI_{new}}}{\mathrm{CEPCI_{Ref}}}\right) \times \left(\frac{\mathrm{Location\ Index_{new}}}{\mathrm{Location\ Index_{Ref}}}\right)$$

Where FCI = Fixed Capital Investment (new and reference)

Capacity = the capacity of the plant

n = scaling factor

CEPCI = Chemical Engineering Plant Cost Index

Location Index = location adjustment is performed when the location of the reference and proposed plants differ

The capacity was adjusted to account for the differences between the proposed plant and literature production capacities. The scaling factor ‘n’ accounts for the so-called economies of scale: the non-linear relationship between facilities with similar technologies and various capacities; refer to Table 2-15 for scaling factors based on the type of industry. This factor is either based on the product or processes that are considered. A value of n closer to 1 represents an increase in capital costs proportionally increasing with plant size. However, values less than one indicate economies of scale exist, and capital investments decrease as plant size increases. In instances where the value is greater than 1, diseconomies of scales are present. This implies that if the scaling factor is greater than 1, economies of scale do not exist; rather, diseconomies of scale exist and the incremental cost becomes more expensive for every added unit of capacity. A scale factor of exactly 1 indicates that a linear relationship exists and there is no change in the incremental cost per unit of added capacity. A scale factor of 1 also indicates that it is just as economically feasible to build two small facilities as one large facility with the same capacity.

Table 2-16: Scaling factors for different chemical engineering processes (Remer & Chai, 1993)

Industry	Average n
All values from different sources and processes	0.67
Chemical plants and processes	0.67
Gases	0.65
Polymers	0.72
Biotechnology	0.60
Power plants, effluent treatment, drinking water, refrigeration	0.75
Miscellaneous	0.70

The CEPCI (Chemical Engineering Plant Cost Index) accounts for inflationary changes between years (composite index, developed for the USA process industry). A location adjustment is performed when the location of the reference and proposed plants differ. The location factor considers the differences in equipment, productivity, labour costs, commodities, duties, freight, taxes, procurement, etc. Lastly, time and currency adjustments are performed considering the two plants' year and currency under investigation. Peters et al. (2008) further add that a contingency factor should be included to account for errors. For Fixed Capital Investment (FCI) new, the contingency is calculated at 5% of the initial FCI, and the Working Capital (WC) is calculated at 10% of FCI (Naidoo, et al., 2019).

2.6.3. Operational Expenditure (OPEX)

The operational costs include the fixed and variable expenses incurred directly or indirectly through the daily running of the process. The variable costs are dependent on the quantity of product, while fixed costs remain constant irrespective of throughput. Therefore, operational costs associated with fixed and variable costs and general expenses are considered to calculate the total annual operating cost.

2.6.4. Discounted Cash Flow (DCF)

A DCF analysis is an appraisal method used to assess the value of an investment based on its expected cash flows in the future. The results from the CAPEX and OPEX calculations inform the DCF analysis. According to the time value of money, the future value of money decreases. A discount rate, often 20%, estimates the present value of an investment by considering the expected cash flows. Investors can utilise the present value of money to find whether the project’s future cash flows are equivalent or greater than the initial investment value: a higher value than the current cost of the investment indicates that a project should be considered (Fernando, 2020). The Net Present Value equation for the DCF is presented by Equation 2-10.

Equation 2-16

$$\sum_{n-1}^{n\to t} \frac{\mathrm{NPV}}{(1+\mathrm{r}')^{\mathrm{n}}} = 0$$

Where, NPV = Net Present Value

r = discount rate

n = time of the cash flow

The Net Present Value (NPV) is useful (calculated by Equation 2-11), especially for long project periods (between 10-20 years) that have high inflation rates or where prices are not linear. The NPV should have at least a value of zero, meaning the investor recovers costs over a project period. A positive NPV indicates that the project value has increased at the end of the project lifetime. In contrast, a negative NPV means that the project undertakes losses over its lifetime, and thus it is not economically feasible (Fivga & Dimitriou, 2018).

Equation 2-17

$$\text{Net present value (NPV)} = \frac{\text{Estimated net cash flow in year n}}{(1+\mathrm{r})^{\mathrm{n}}}$$

Where, n = year of interest

r = discount rate

The IRR is the average annual return rate on the initial capital investment considering all costs and expenses throughout the project period, at which the NPV is zero. The IRR is evaluated on the present value of money and allows the assessment of profitability (Lauer, 2008). As a result, the investors will receive a return on their investment, equivalent to the IRR each year of the project. For a project to be an attractive investment that considers the degree of risk associated with the investment, the IRR should be higher than the discount rate.

The Payback Period (PBP) is the number of years for the project to recover the initial investment. The PBP is calculated by Equation 2-12. In practice, the maximum acceptable PBP is often chosen as a fixed value, e.g., three years. In some cases, the limit value of the PBP has been related to the economic life of the investment, e.g., a PBP shorter than half the economic life (Yard, 2000). If these two rules of thumb are combined, a more theoretically correct evaluation of investments can be achieved. Since the decision situations in the evaluation of capital investments typically are uncertain concerning the time pattern and the duration of the cash flows, this can justify the use of a simple but more robust PBP method even if there would be time for more advanced analyses.

Equation 2-18

$$\mathrm{PBP} = 0.85 \times (\ \mathrm{MARR} + \frac{1}{\mathrm{N}})$$

Where, PBP = Payback period

MARR = Minimum Acceptable Rate of Return

N = Year of interest

The Minimum Acceptable Rate of Return (MARR) is usually set as the lower limit for investment considered acceptable by the investor. The MARR was not investigated in this study but may serve as an informative parameter for an investor considering the current interest rate and expenses when obtaining funds (Smith, 2005).

If the NPV is favourable, the DCF IRR will necessarily be advantageous and the actual earning rate of the investment. The two methods are always used together, providing an excellent method for making economic decisions because it includes all the other relevant information methods and accounts for the time value for money.

2.6.5. Sensitivity Analysis

The influence of various parameters can be determined through sensitivity analysis. This entails varying the parameter in question while keeping all other parameters static. The goals and scope are connected to the sensitivity analysis results, generally linking high sensitivity with high-quality demand.

2.7.Impact Assessment

Three key pillars often describe sustainability: economy, environment, and society, sometimes referred to as the triple ‘P’ of people, planet, and profit (Sloogweg et al., 2010). Over the years, there has been a desire to integrate environmental, social and economic aspects in assessment plans, programmes and policies to form an integrated framework. The environmental impact, social impact and economic cost-benefit analysis largely continue to operate separately and experience great difficulty working in a multidisciplinary environment (Sloogweg et l., 2010). A conceptual framework includes all potential effects of human interventions on the biophysical and or society; the environment is presented in Figure

2-20. Although some of the aspects will be considered in the impact assessment in this dissertation to determine some environmental, technical, and societal impacts of chosen technologies, it will be less comprehensive and contain simple quantifications to rank each technology against one another.

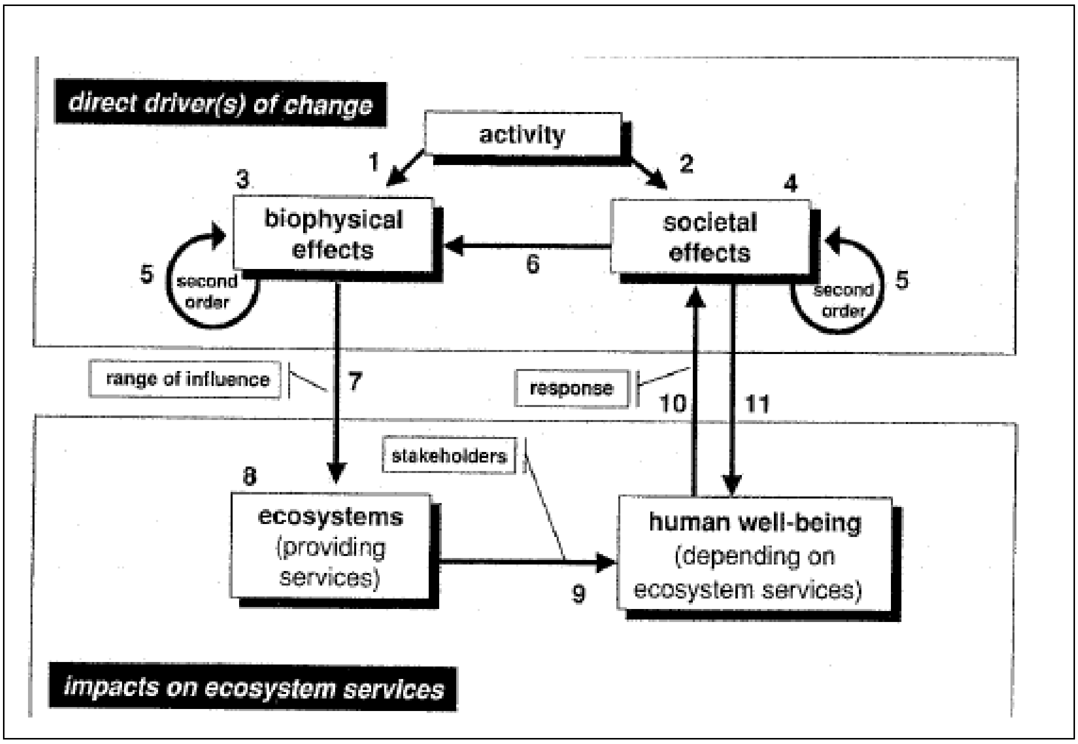


Figure 2-20: Impact assessment framework by Slootweg et al. (2010)

Examples of impact assessment in South Africa include the environmental Impact Assessment (EIA) and socio-economic impact assessments (SEIAS). The EIA is largely a decision-making tool to determine the impacts (positive and negative) based on a proposed course of action and thereafter select the best practicable course of action (DEA, 2020). The SEIAS intends to determine the impact on social cohesion and security (food, safety, financial, energy etc.), economic inclusion, economic growth and environmental sustainability (DPME, 2015). However, South Africa is trying to incorporate social aspects in more legislative innovations.

2.8. Knowledge gaps

Through an intensive literature review, multiple knowledge gaps were identified. Municipalities and industries venturing into such technologies would be encouraged to share information, promote the uptake of alternative solutions, and support the move away from landfilling within the country. In general, little information exists on improperly disposed waste, leading to a gap in quantifiable rural waste data for areas lacking service delivery.

During this study, due to COVID-19 restrictions, sampling studies were not possible, and waste characterisation is based on previous assessments and data readily available from respective municipalities. Furthermore, South Africa largely disposes of waste in landfill due to the relatively low (apparent) costs involved.

Operations data for the different technologies were not readily available. This study highly dependent on previous studies. However, it should be noted that this assessment uses these technologies as examples. Therefore, if and when more recent reliable data becomes available for a given location, these can easily substitute the current data set in the models, and increased accuracy of such a feasibility study will result.

Expertise in waste management, in general, is lacking within the country, and policymakers must consider such studies to inform and assist municipalities.

CHAPTER 3: METHODOLOGY

This chapter introduces the methodology followed in undertaking a techno-economic analysis and impact assessment of waste treatment options (viz. composting, AD, and pyrolysis).

A desktop analysis was conducted by collecting the appropriate information from reports and studies of diverse individuals, government entities, internationally published research, independent agencies, and installed plant data. An integrated excel spreadsheet was developed and used to perform the necessary calculations to determine the economic outlook of appropriate technologies. Finally, the impacts of these technologies were investigated through an impact assessment. For this study, a brownfield operation of the treatment plant is considered. For eThekwini, the Garden Route District Municipality (GRDM) and Calvinia, the facility is appended to an existing landfill site. Hence, land, site development and infrastructure costs are omitted from the assessment in all instances.

Waste treatment options like composting, anaerobic digestion, and pyrolysis can unlock waste pathways that have been previously excluded due to the generally low cost of landfilling. Following these alternative pathways, waste will be diverted from landfills mitigating environmental hazards and decreasing greenhouse gas emissions. The three locations of Calvinia, Garden Route District Municipality and eThekwini were selected as examples for the effects of population dynamics on waste volumes and compositions in the country. Calvinia represents a decentralised scenario and compares results at larger municipalities (GRDM and eThekwini). The waste sector can further promote job opportunities and mitigate the energy crisis, especially in rural areas. Decentralised treatment options offer an alternative to standard high-cost solutions such as landfilling and mass incineration. These treatment options are assumed to be smaller, less complex, and readily available options.

3.1.Rationale for selection of locations and estimation of respective waste volumes

As previously discussed in section 2.1, socioeconomic factors vary throughout South Africa, resulting in service delivery disparities. Furthermore, the population and poverty dynamics tend to dictate where most services are aimed: more populated areas, considered economic hubs, receive more attention than rural areas. Although most municipalities strive towards adequate waste management, apparent differences are noticed. This dissertation aims to provide techno-economic assessments in dependence of different plant sizes, taking into account the specific conditions of the respective serviced municipality. As a result, the locations of Calvinia, the Garden Route District Municipality (GRDM) and eThekwini were selected. These locations vary in population and thus waste composition, generation and services. The following considerations and assumptions are made:

Calvinia had a population of 9 680 people in 2011 (Frith, 2011) and an estimated annual waste generation of 1 600 tpa (Nell and Schenck, 2018). Although it is acknowledged that the rural population declines in South Africa, with 0.06% between 2011 and 2020 (Macrotrends, 2021), this was not considered relevant, and hence the 2011 data was used for the 2020 assessment. The waste composition of Calvinia was determined by Nell and Schenck (2018) and grouped into categories as shown in Table 3-1.

For the GRDM, the waste available at the PetroSA landfill site was considered. The landfill receives waste from four local municipalities: George Local Municipality, Knysna Local Municipality, Bitou Local Municipality and Mossel Bay Local Municipality. In the absence of direct landfill data, the average waste compositions from these local municipalities were used to determine the waste profile that would best describe the PetroSA site (from Table 2-8 to produce data shown in Table 3-2). The total waste from the four municipalities was 7 213.55 tpm (86 562.6 tpa) in 2018/2019. The population data for 2019 was 622 664 (Garden Route District Municipality, 2019), decreasing to 621 454 in 2020 (Garden Route District Municipality, 2020), a 0.23% decrease. The decrease in population was considered negligible, and hence the 2018/2019 data was used for the 2020 assessment.

The waste generation from Mariannhill landfill was 122 514 tpm (2010) (Jagnath, 2010), the population increased from 2010 (3 514 968) (Coperative Governance and Traditional Affairs, 2020) to 2020 (4 004 603) (eThekwini Municipality, 2020), a 14% increase, resulting in the escalation of the waste volume to 139 352 tpa (2020). The waste composition profile provided by Jagnath (2010) was applied to the waste volume and is shown in Table 3-2.

The waste compositions detailed in section 2.1 were derived by different waste study methodologies resulting in different waste categories. To ensure consistency between the different locations and for use in further calculations, Table 3-1 was designed to compare the various waste categories. The waste fractions were grouped under the umbrella categories (‘waste category’). The composition by weight was calculated by taking the sum of the waste types under that category.

Table 3-1: Groups of reference waste categories

Waste category (this study)	Calvinia	GRDM	eThekwini
Reference	Nell and Schenck (2018)	GIBB Engineering and Architecture, (2019 (a-d))	Jagnath (2010)
Biogenic Waste	Food/compost; Garden waste	Food Waste; Garden	Biogenic Waste, Garden Refuse
Glass	Glass	Glass	Glass
Metals	Metals	Metal	Metal (Tin/aluminium)
Paper and cardboard	Paper and cardboard	Paper; Cardboard	Paper and Cardboard; Other paper, Scrap boxes and cardboard
Recyclable Plastics	Recyclable Plastics	Soft Plastics; Hard Plastics	LDPE; HDPE; PET; PP; PS
Non-recyclable Plastics	Non-recyclable Plastics PS		PS
Other	Medical Waste, E-waste, Others	Nappies, E-Waste, Textiles; Hazardous; Rest; Wood	Other

In the absence of reliable data for separation at source of recyclables, it was further assumed that although some separation at source already takes place in the above municipalities, the diverted waste volumes are currently negligible. Table 3-2 displays the escalated waste generation and compositions used in all further analyses.

Table 3-2: Waste data inflated to 2020 for Calvinia, GRDM and eThekwini

	Calvinia	GRDM (PetroSA)	eThekwini (Mariannhill)
Waste Ref (tpa)	1 600.0	86 562.6	122 514.0
Waste 2020 (tpa)	1 600.0	86 562.6	139 352.3
Biogenic (wt %)	33.0	30.6	47.2
Glass (wt %)	12.5	8.3	8.2
Metal (wt %)	4.0	3.4	4.9
Paper and CB mixed (wt %)	13.2	15.3	16.2
Rec Plastic Mixed (wt %)	14.5	16.9	13.8

	Calvinia	GRDM (PetroSA)	eThekwini (Mariannhill)
Non Rec Plastic Mixed (wt %)	4.6	0.0	0.9
Other (wt %)	22.9	25.5	9.7

3.2.Material Flow

In order to correctly allocate costs, it is required to understand the material flow. Before treatment, the costs for sorting, recyclate transport and revenue streams from landfilling and recyclate sales are considered to determine the feedstock cost for each treatment option based on the mass balance according to the treatment path described by each scenario.

The four different scenarios are:

1. The waste is separated, with an efficiency of 80%. Recyclate is sold to BBC, and the remaining fractions are forwarded to the landfill.
2. The individual technologies are assessed, where the waste is separated, the respective waste fraction is treated (2(a) composting, 2(b) AD and 2(c) plastic pyrolysis), the fractions that can be sold as recyclate are forwarded to BBCs, and the remainder is disposed of in the landfill site.
3. The plastic pyrolysis is reassessed under certain assumptions based on reduced waste availability due to the implementation of the EPR.
4. A combination of technologies is assessed without considering the impacts of the EPR, where after sorting, two technologies processing different fractions are combined (4(a) composting and pyrolysis and 4(b) AD and pyrolysis), the remaining recyclates are being sold, and the remainder forwarded to landfill.

3.2.1. Scenario 1: Assessment of separation and recycling

This scenario considers the sorting and recycling of waste streams. All waste entering the landfill (based on Table 3-2) is sorted (80% efficiency (CBI Environmnetal Infrastructre, Inc., 2017)), and after that, recyclate streams are forwarded to BBCs, and the remaining waste is landfilled.

The typical recyclable streams in waste are paper, cardboard, plastic, metal and glass. The literature data for the selected locations lacked in describing the fraction of recyclable and non-recyclable streams in most cases. For this reason, the following assumptions were considered:

- For Calvinia, all recyclable plastic will proceed to recycling while non-recyclable plastics are sent to landfill. All metal, glass, paper and cardboard are sent to recycling. The metal fraction is considered to consist mainly of aluminium cans.
- For the GRDM, all soft plastics (8.5%) and hard plastics (8.4%) are recycled. This underestimates the non-recyclable content in the waste stream, as some of the hard and soft

plastic will, in reality, not be recycled and will be landfilled. All other recyclable streams will be recycled.

- For eThekwini, all plastics excluding PVC (added to ‘others’) are recycled, and all other recyclable streams are recycled.

The material flow diagram of key streams is presented in Figure 3-1, with the accompanying mass balance in Appendix C, Table C-1.

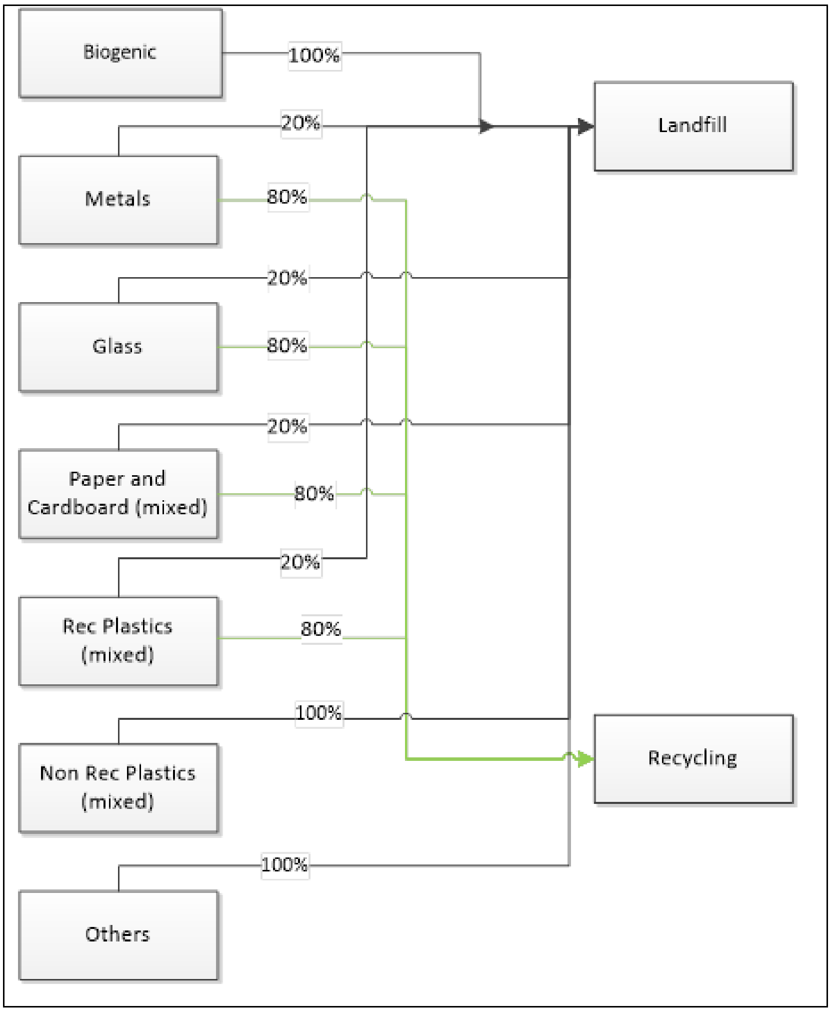


Figure 3-1: Material flow diagram for scenario 1: Separation

3.2.2. Scenario 2(a) and (b): Assessment of specific scenarios

The individual scenarios are dependent on the treatment processes investigated, described as follows:

<u>Composting or AD</u>

All treatment options that process biogenic (organic) waste follow the same path. The biogenic materials are processed by composting or AD. As discussed above, the recyclable streams are sent to the BBC and ‘others’ that are non-processed or non-recyclable material proceeds to landfilling. The material flow diagram is presented in Figure 3-2, and the mass balance is shown in Table C-2.

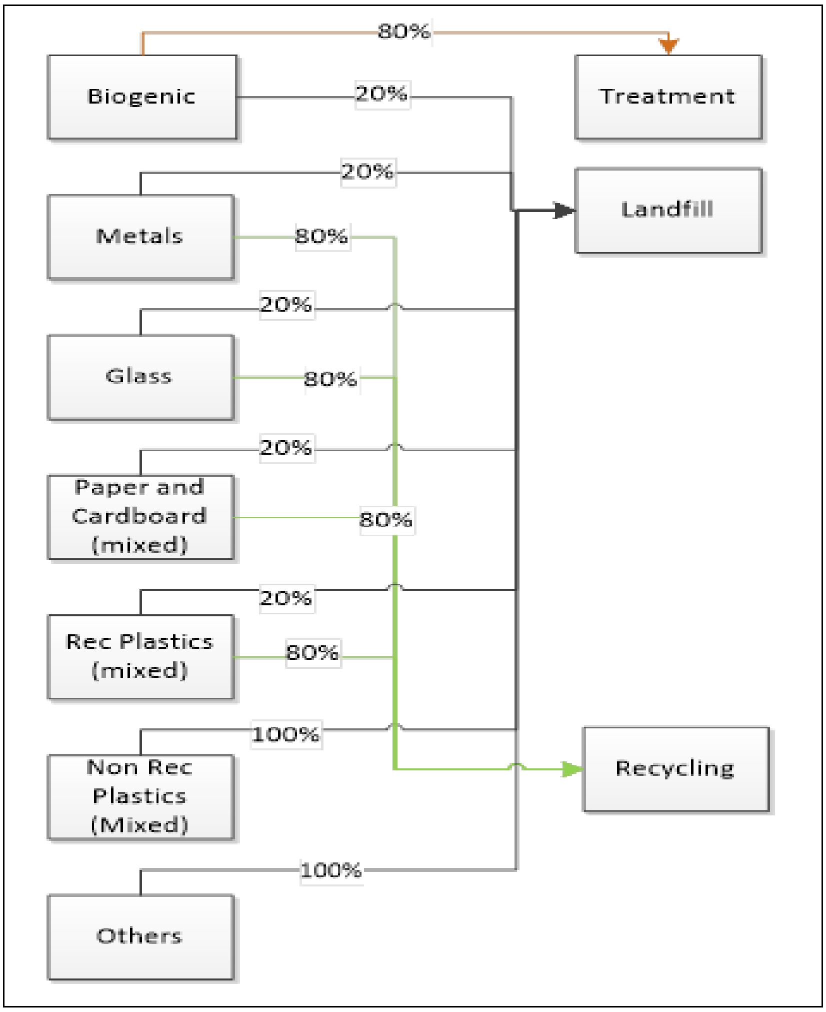


Figure 3-2:Material flow diagram of biogenic treatment options (scenario 2(a) and 2(b))

Pyrolysis

The pyrolysis process accepts mixed waste plastic as the feed, including the recyclable and non-recyclable plastics fractions. Contrary to the previous scenario, where the non-recyclable plastics fraction was added to the ‘other’ stream and sent to the landfill, pyrolysis diverts all plastics to processing to produce pyrolysis oil as a product. The other recyclates (i.e. paper and cardboard, metals and glass) are recycled. All other non-process streams, i.e. the biogenic waste and ‘others’, are forwarded to landfilling. The material flow diagram describing the process is presented in Figure 3-3, and the mass balances are shown in Table C-3.

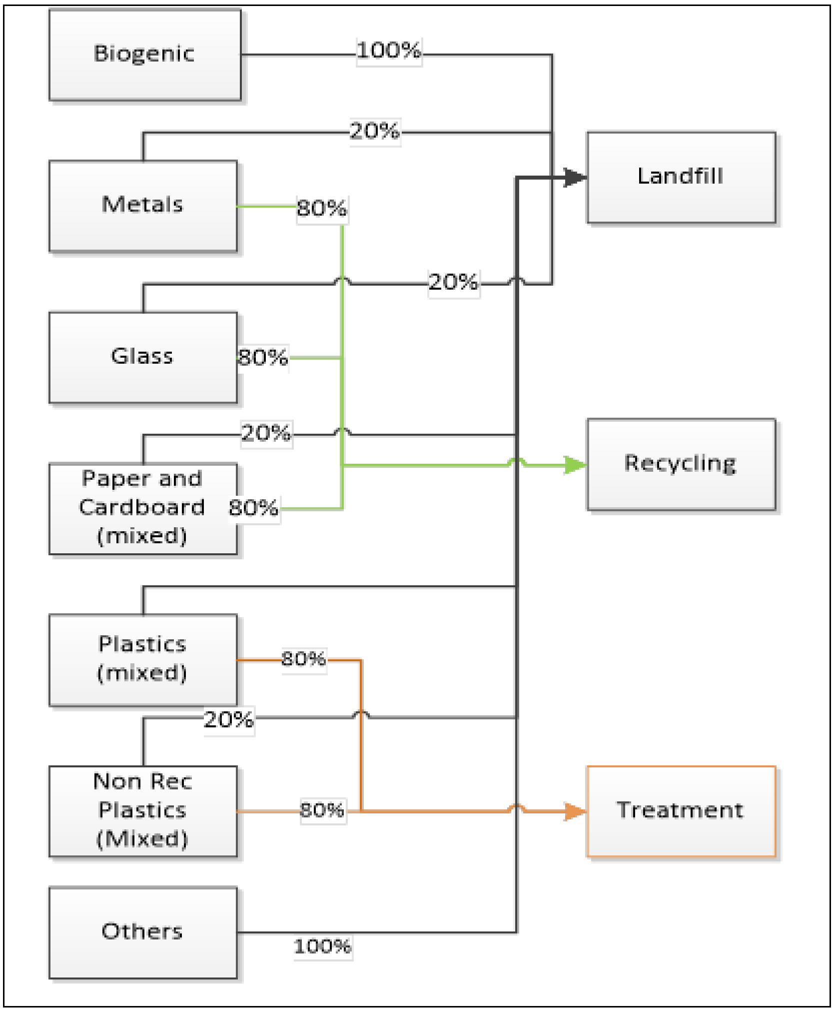


Figure 3-3: Material flow diagram of pyrolysis of plastic waste (scenario 2(c))

3.2.3. Scenario 3: Implementing EPR in collection rates

The newly gazetted EPR regulations are expected to change the country's current waste generation, collection and recycling patterns. In line with the EPR, recycling targets are defined for specific packaging products that currently make up significant compositions in household waste. The targets for waste fractions of interest are presented in Table 3-3. To meet these goals, waste will be diverted through collection initiatives and eventually, most likely, be met by harnessing the recyclate in municipalities. Consequently, the total waste available by each location will decrease by the EPR targets for the respective years once implemented. However, this might not be the case, and some areas might have higher targets than others resulting in disproportionate recycling rates. For purposes of this dissertation, it is assumed that each location will meet the recycling targets within the proposed year.

The EPR regulations are assumed to be implemented in 2022, with the first mandatory recycling in year four (2024) of operation. Mandatory recycling targets of each waste stream, as specified by Table 3-3, will be implemented in this study by diversion after separation at the landfill site, rather than through separation at source. Hence, the EPR targets will not reduce the amount of waste delivered to the separation facility. For all recyclable streams, the available recyclates were assumed to be sold at BBCs, this means that all EPR targets will be met at year one of implementation. Therefore, the only process scenario that will be affected is pyrolysis. Since all plastic waste was sent to processing when the EPR kicks in, a certain percentage will now have to be recycled, reducing the amount of pyrolysis feed stream available.

The possible waste streams affected by the EPR regulations, as discussed in section 2.3.5 – Table 2-3, are presented in Table 3-3 based on plant years. As seen, the waste categories in Table C-6 are much more detailed than the respective waste categories in Table 3-2. For this reason, assumptions are required to determine the fraction of waste that will be affected by the EPR. Greencape (2020) provided data on the amount of material in circulation (virgin/recyclables). This data was used to determine the percentage of each waste category for that group. For example, assuming that the total plastics consist of PET (beverage bottles), PET (thermo-form), LDPE, HDPE, PP, PVC, PS, then the fraction of PET (beverage bottles) can be determined. In other words, the total plastic stream for each location is assumed to contain the respective fractions based on Table C-7.

Table 3-3: Assumed EPR targets (given in percentages) for further calculations for the plant project years

Year	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
Production year (starting 2021)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Year since EPR implementation	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Glass (all)	*	*	*	38	43	48	53	54
Metal Aluminium (non ferrous cans)	*	*	*	30	32	33	34	35
Plastic PET Beverage bottles	*	*	*	54	58	59	61	65
Plastic PET Oil Bottles	*	*	*	6	12	23	29	35
Plastics thermoformed PET				8	12	17	24	30
Plastic PET (Flexible)				9	18	27	36	45
Polyvinyl Chloride (Rigid and flexible)				5	5.5	6	6.5	7
Polystyrene (expanded and high impact)				20	25	30	36	43

Year	2021	2022	2023	2024	2025	2026	2027	2028
Production year (starting 2021)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Year since EPR implementation	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Single Use Products (PS, HDPE, PET and PP)				30	35	40	45	50
Newspapers				35	40	45	50	55
Magazines				33	34	36	38	40
Office and graphic paper – mixed and other paper				58	63	68	73	80
Corrugated cases/ kraft papers				58	63	68	73	78

** waste volume and composition remains constant; 80% recovery assumed. According to assumptions, streams in green represent that the EPR targets have already been met within the first year.*

3.2.4. Scenario 4(a) and (b): Combined Scenarios

For the two combined scenarios of 4(a), composting and pyrolysis, and 4(b), AD and pyrolysis are considered, with each scenario following the material flow given in Figure 3-4. The combination of individual mass balances applies where the process stream now diverts both biogenic and plastic waste simultaneously to the two processes. See Table C-4 for mass balance.

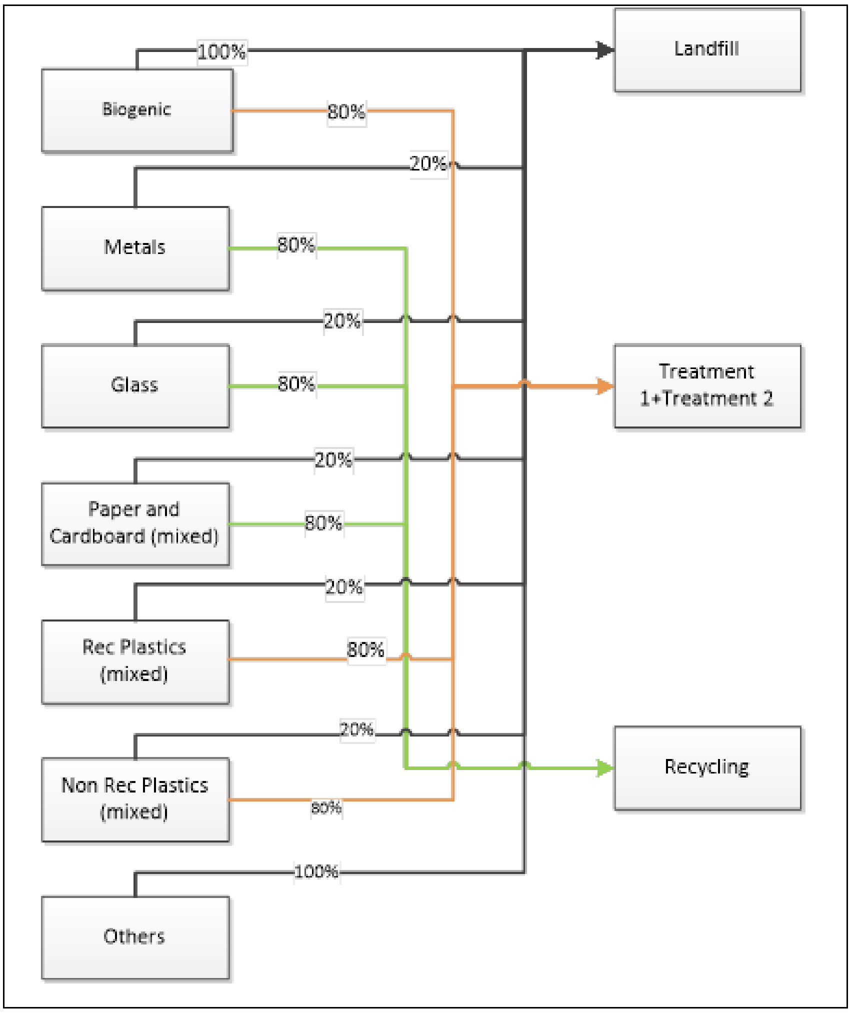


Figure 3-4: Process flow diagram of combined scenarios (Scenario 4(a) and 4(b))

3.3. Cost Allocation

In general, the raw material cost of the individual waste fractions is equal to the costs of waste collection at the individual households, its transport to the landfill site, and the sorting. Waste collection and transport costs are inherently difficult to determine, as distances and population densities vary. Additionally, waste collection is free for indigent people. Therefore, it is herein assumed that the households currently cover the cost of collection, transport and landfill via the monthly collection fee. In other words, mixed waste is available free of charge at the landfill site. Any waste diverted from landfills will accrue costs for sorting (see section 3.3.1.), recyclate sales (section 3.3.2.), transport costs for recyclables (section 3.3.3.) and credits for reduced landfill volumes (3.3.4.).

3.3.1. Sorting costs

The waste, as delivered from the collection from households, is assumed to be separated at the landfill site to provide fractions that are forwarded to sales (as recyclate) or the waste treatment plant options. Sorting can be done manually or mechanically. Manual sorting minimises the costs of separating the waste into different fractions and creates job opportunities for community locals. However, the additional equipment required for manual sorting is unknown and can be best approximated by labour costs. The mechanical separation system processing municipal solid waste costs between R80 and R100 per ton of processed waste depending on the level of automation (Purser, 2011). Purser (2011) found that a country-specific cost of R90 per ton of waste processed (before inflation) can be considered. Since the cost of waste sorting is not explicitly known, the implications of higher or lower costs will be a key parameter of interest in the sensitivity study.

The sorting costs were inflated to provide a current representation of these costs. The inflation method is described presented in Appendix C.2 using the PPI and CEPCI. The deviation between the PPI- and CEPCI-based costs for the mechanical sorting was 91%. Therefore, for the TEA, an average value between PPI- and CEPCI-derived values is taken into account (Table 3-5). The PPI derived value (R185.96), the CEPCI derived value (R141.8) and the EPR values (R93.5) are discussed in the sensitivity analysis to determine the varying effects on the scenario feasibility.

3.3.2. Recyclate sales

Recycle fractions were described in section 3.2.1. The revenue from plastics was approximated by 'mixed plastics' for recyclable plastics; paper and cardboard by 'mixed paper'; metals by 'cans'; and glass by 'glass' from Table 2-15. The prices for the three specific locations of this study were not explicitly available. Therefore, the average prices from all locations provided a national average for each product. The values from 2012 were recorded by Viljoen et al (2020) and were hence inflated to give a current representation. The inflation method is described in Appendix C.2 using the PPI and CEPCI indices. The results are shown in Table 3-4. The deviation between the PPI- and CEPCI-based costs for the recyclates was 40%. Therefore, for the TEA, an average value between PPI- and CEPCI-derived values is taken as the recyclate revenues cost (Table 3-4). The lower CEPCI values were considered in the sensitivity analysis, the lower limit revenues for the recyclates, while the higher PPI values were taken as the higher limit revenue.

With the EPR just having been gazetted, it is yet to be seen how the recyclate markets will develop in the future. However, the EPR implementation enforced the regulation of recyclate prices with certain companies providing indicative fees. The indicative fee for some plastics has become available, namely from PETCO (PETCO, 2021), providing the current indicative EPR fee of post-consumer plastic waste streams, in Table C-5. For all waste plastic streams listed, the fee is R565, except "PET shrink/PET flexible", which is R2 500/t. This means that plastics recyclate prices increased by 3.91% between 2012

(543.75 R/t) and 2021. This percentage was also applied for the other recyclate streams for this study. These prices were in good agreement with the CEPCI derived values in Table 3-4 and will be reflected in the sensitivity analysis.

Table 3-4: Cost and revenue values used in the study for mechanical sorting (Purser, 2011), recyclate costs from 2012 (Viljoen, et al., 2021) using PPI and CEPCI (Chemengonline, 2020)

Unit (year)	**Mechanical sorting**	**Mixed paper**	**Mixed plastic**	**Metals (cans)**	**Glass**
R/t (2010)	90				
R/t (2012)		319.23	543.75	593.85	230
PPI-derived values					
R/t (2020)	185.96	455.5	775.8	847.3	328.1
CEPCI-derived values					
R/t (2020)	97.4	325.6	554.5	605.6	234.6
Deviation (%)	91	40	40	40	40
R/t (2020) Average	**141.8**	**390.5**	**665.2**	**726.5**	**281.3**
EPR values according to PETCO (3.91% increase)					
R/t (2021)	93.5	331.7	565.0	617.1	239.0

3.3.3. Transport of recyclables

Since the prices of transporting recyclables are not explicitly published or easily calculated, these costs were estimated from the cost of transporting materials for the distance travelled as described by fleet watch benchmarks (Braun, 2019). However, the fuel price was significantly lower in August 2019. Furthermore, the literature costs are operational and may not consider the capital investment for the truck (meaning that truck hire might be more expensive to cover this budget item). The estimate taken from the literature is assumed to be lower than current actual rates and will be further investigated through a sensitivity analysis.

Since Calvinia is the furthest away from a BBC, assuming a long haul using a cargo truck to transport the recyclable material, costs range between R1.64 to R3.28 per ton per km (Braun, 2019). The lower value of R1.64 per ton is used, assuming that only when there is enough material for a full load ofthe recyclates be transported, either in one or multiple loads throughout the year. For GRDM and eThekwini, BBCs are assumed to be closer by and may be depicted by a short-haul in metro areas; these costs range between R4.50 to R9.01 per ton per km (for a full and 50% load, respectively) (Braun, 2019). Full loads are assumed, and the cost of transporting recyclables in these areas is costed at R4.50/ton/km. The distances are 400 km, 150 km and 100 km for Calvinia, GRDM and eThekwini. A sensitivity analysis will be conducted to determine the effect of distance on recyclables revenue. These trips are considered one-way trips, and return trips are not accounted for if any are required. It is assumed that the costs include truck and haul requirements for the length of the journey only.

3.3.4. Landfill costs and credits

Landfill space is a limited good in metropolitan areas and can be assigned a value. Waste diverted from the landfill, either by sorting and selling recyclate or diversion to the treatment options considered here, gives rise to credits: As stated above, the costs for collection, transport and landfill are covered via the monthly collection fee paid by households. Assuming that municipal waste management is a non-profit operation, the diversion of waste from landfills hence incurs a credit of the proportion of the collection fee. In other words, the concept of "prime costs" is applied, meaning that the cost for the consumer is the proportionate production (here: waste disposal) costs that the producer (here: municipality) has incurred, without a profit margin. This costing approach assumes that the tariffs for household disposal and the landfill costs described above are the actual costs the municipality is handing over to the citizen, i.e. no profit is being made. The landfill gate fee is considered as credit towards diverting waste away from landfills, therefore positively influencing the balance sheet.

In the absence of data regarding the respective contributions of collection, transport and landfill costs to the fee, the current work estimates these from published landfill gate fees. However, since gate fees for Calvinia and GRDM were not accessible for 2020, the value for the city of Cape Town is used while the gate fee for eThekwini municipality was available (Table 3-5). It should be noted that the gate fee for Cape Town is relatively high, and for a rural area such as Calvinia, the gate fee is expected to be much lower. Hence, a sensitivity analysis is applied to the landfill credit to determine varying fees' effects on the process feasibility.

Table 3-5: Waste disposal fee/landfill tax for 2019/2020

Location	2019/2020 (including VAT)
City of Cape Town (R/ton)	584
eThekwini Municipality (R/ton)	417

3.3.5. Summary of the Cost Allocations

The cost for the production of individual sorted fractions from waste is determined by allocating 1.) the mass-weighted sorting costs, 2.) the landfilling credit incurred by the fraction for not being land-filled (if applicable), 3.) the cost of transport of recyclate to the BBCs (if applicable), and 4.) the recyclate sales at BBCs (if applicable). The costs and credits for each location are presented in Table 3-6.

Table 3-6: Costs (-) and credit (+) data for each location

	Calvinia	GRDM	eThekwini
Sorting (R/ton)	-141.80	-141.80	-141.80
Landfilling (R/ton)	+584.00	+584.00	+417
Recyclate transport (R/ton)	-656.00	-675.00	-450.00
Glass recyclate (R/ton)	+281.30	+281.30	+281.30
Metal recyclate (R/ton)	+726.50	+726.50	+726.50
Paper recyclate (R/ton)	+390.50	+390.50	+390.50
Plastic recyclate (R/ton)	+665.20	+665.20	+665.20

An overall positive value indicates that the costs for sorting and transport of recyclates are lower than the income generated from landfilling credits and recyclate sales. For scenarios 2 to 4, a feedstock cost had to be determined for the treatment plant. For this purpose, the sorting cost of any fraction that is neither processed in the treatment plant nor sold to BBCs but landfilled was allocated on a weight basis to the recyclate fractions and the fraction serving as feedstock in the treatment process. This is detailed in Appendix C.4. In cases where the sum of the sorting costs of the feedstock fraction and landfilled fraction was lower than the landfilling credit for the feedstock fraction, the feedstock cost is a credit for the treatment plant's operational costs of the TEA.

Similarly, the recyclate costs comprise the mass weighted cost for sorting, transport to BBCs, sales of recyclates, credits for landfill savings, and the fractional cost of the sorted and landfilled fraction (see appendix C for calculations). Dependent on the scenario, these were revenues or expenditures. The recyclate cost was added to the income of the product generated in the treatment plant.

For scenarios where the biogenic waste fraction was treated (composting, AD), the untreated feedstock fraction in years 1-3 incurred additional landfilling costs (for the 30, 20 and 10% of the biogenic fraction not processed when the plant is not yet operating at full capacity), which was taken into account in the undiscounted income within the TEA. For scenarios where the plastics waste fraction was treated, the untreated fraction in years 1-3 was forwarded to recycling via BBCs (incurring both transport costs and recyclate sale revenues), which were accounted for in the TEA.

3.4.Process Assumptions

The assumptions required to complete the CAPEX and OPEX calculations differ for each process further described in this section.

3.4.1. General Assumptions

- At years one to three (2021-2023) of operation, 70, 80, 90%, and 100% from year four onwards of the sorted waste fraction is assumed to be processed, respectively, until the plant has developed the full capacity with which it would operate from thereon.
- The literature indicates that the economic life of composting is relatively low. On the other hand, WTE (AD, pyrolysis and gasification) projects usually have an economic life of between 20 and 25 years (Mabalane, 2020), while other authors give the lifespan of AD, incineration and gasification as 20 years (Purser, 2011). However, as discussed in section 2.4., the Municipal Systems Act has a lifespan of three years, and prolonged economic life could result in an unfavourable selection of these projects at a municipal level. For this reason, a lower project life of 15 years for all treatment options was assumed.
- Transport costs of waste have not been explicitly considered but are assumed to be covered by the domestic waste collection fee paid by households. This allows for a comparison of treatment options at the point of availability, the landfill site.
- The cost of land space was not included since the technologies are assumed to be situated close to or within the landfill.
- The design and construction phases are assumed to be completed, and the facility will become operational in 2021, i.e., year 0 presenting 2020.
- From year one, depreciation is calculated by the straight-line method.
- The scaling factor, i.e., the ratio of the available waste fraction to the waste volume that could be processed in tons, is assumed at 85%.
- An 80% sorting efficiency is assumed (that is, the amount of waste that results in usable fractions) (CBI Environmnetal Infrastructre, Inc., 2017). The cost of mechanical separation is assumed to be R141.80/t of processed waste, and each sorter is estimated to handle a 2.6 t/8-hour shift (CBI Environmnetal Infrastructre, Inc., 2017).
- Any benefits from land savings and reduction of GHG emissions and, therefore, reducing air pollution were disregarded.
- The total production costs were taken to inflate at 1% annually.
- The income tax rate was assumed as 28%.
- A 20 % discount rate (annual compounding) was assumed.
- The MARR was considered as 20%.

- In light of the global COVID-19 pandemic, the WEF global competitiveness report 2020 with the country-specific location indices was not published (WEF, 2020). Hence, the 2019 data was used.

3.4.2. Assumptions for Composting: Scenario 2(a)

- The average CAPEX cost for the DAT composting process was R2 400 000 in 2007 for a feed rate of 180 tpd of biogenic material. A total of eight operators are required: six sorters and two supplementary feed workers.
- The capital cost includes any planning, engineering and construction, source separation, and the capital cost of the equipment.
- The scaling factor used for preliminary CAPEX calculations has not been explicitly identified in the literature, with no literature stating the value. The average scaling factor of 0.67 should provide a fair estimate for different processes, in line with the values given for biotechnology processes (0.6) and chemical processes (0.67), see Table 2-15.
- The input assumptions for composting for each location is provided in Table 3-7. The feedstock is a biogenic waste.
- As per Reddy (2016), a compost degradation factor of 0.75 was used.
- Compost will be sold at R150 per ton, which falls within the range indicated (Jagnath, 2010).
- The process is assumed to operate 313 days a year for 8 hours a day for composting.

Table 3-7: Reference data for different composting facilities (Reddy, 2016)

Parameter	Composting	Reference
Cost of unit	R2 400 000	(Reddy, 2016; Jagnath, 2010)
Feedstock	Organic	
Feed rate	180 tpd	
Number of operators	8	
Product	Compost	
Yield (%)	75	
Location	South Africa	
Year	2007	
	CAPEX Data	
Scale factor n	0.67	Assumption
CEPCI ref (2007)	525.4	(Chemengonline, 2019)
Location index (SA)	62.4	(WEF, 2019)
CEPCI new (2020)	596.2	(Chemengonline, 2019)

Parameter	Composting	Reference
Location index new (SA)	62.4	(WEF, 2019)

The number of labourers was determined by taking a linear estimation from literature based on the daily volume of organic waste. For Calvinia, a minimum of one worker was assumed for sorting and supplementary works, which was more than the linear estimation. The number of workers based on reference data is given for each location in Table 3-8.

Table 3-8: Operators required for composting

	Reference	Calvinia	GRDM	eThekwini
Capacity (tpd)	180	1.35	67.65	168.17
Sorters	6	1	3	6
Supplementary workers	2	1	1	2

3.4.3. Assumptions for AD: Scenario 2(b)

- Capital expenditure ranges significantly based on the size and type of system. The capital cost curves investigated by Rapport et al. (2015) were used for estimating the CAPEX. According to Rapport et al. (2015), a scaling factor of 0.5 was used, but for this study, a factor of 0.5581 was used in accordance with the equation from the curve of Tsilemou et al. The capacity, in this case, was based on the feed to the system. The CAPEX cost included plans, engineering and construction, source separation, mechanical handling costs and the capital cost of the equipment (Rapport et al., 2015). The CHP units are included in the capital costs.
- See Table 3-10 for each location details on labour costs based on literature data.
- The electricity price was R1.30 per kWh, based on the National Energy Regulator of South Africa (NERSA) tariff (Mabalane, et al., 2020).
- The biogas potential for electricity calculations is presented in sample calculations (Appendix C.3). The biogas potential by AD was 0.936 m^3/kg on a dry basis, with an energy potential of 20.7 MJ/m^3 of biogas (Gogela, et al., 2017). An electric potential of 36% and CHP system efficiency of 35% was assumed.
- The currency conversion is R15.77/$. See Table B-3.
- For AD and thermal processes, gasification and incineration processes are assumed to operate following the literature data: 313 days (24 hours daily).

Table 3-9: Reference data for AD processes: A (Rapport et al., 2015)

Parameter	A	Reference
Cost of unit	(Figure 2-18)	(Rapport, et al., 2015)
Feed	Biogenic waste	
Number of operators	16	
Product	Electricity	
Location	USA	
Year	2008	
	CAPEX Data	
Scale factor n	0.5	Assumption
CEPCI ref	575.4	(Chemengonline, 2019)
Location index	83.7	(WEF, 2019)
CEPCI new	596.2	(Chemengonline, 2019)
Location index new	62.4	(WEF, 2019)

It was assumed that one project manager, marketing manager, lab technician and receptionist/secretary are required irrespective of the plant size. At the same time, the number of remaining staff was determined through a linear estimation from reference data.

Table 3-10: Operators required for AD process

	Reference	Calvinia	GRDM	eThekwini
Capacity (tpa)	100 000	422	21 176	52 638
Project manager	1	1	1	1
Engineer	1	1	1	1
Marketing manager	1	1	1	1
Equipment operators (tip floor and scale house)	2+2	3	3	2+2
Maintenance technicians	2	1	1	2
Lab technicians	1	1	1	1
Receptionist/Secretary	1	1	1	1
General labourers	6	1	2	4

3.4.4. Assumptions for Pyrolysis of Plastics: Scenario 2(c)

- The CAPEX varies significantly based on the size and type of system used. Pyrolysis is a chemical process with a scaling factor of 0.67 (Peters et al.,2003).

- The capital investment for a waste pyrolysis unit is ₤999 492 for a capacity of 100 kg/h of MPW (Fivga and Dimitriou, 2018).
- Plastic waste (recyclable and non-recyclable fractions) is the feed.
- The plant operates 7 032 hours annually, 293 days for 24 hours.
- The price of pyrolysis fuel in South Africa is not readily available; however, an interview with Whyte (2020) indicated an approximate price of pyrolysis fuel as R6/L, taken as the fuel price for this study. The pyrolysis system examined in this study converts plastic waste to a heavy fuel substitute or a petrochemical feedstock.
- The conversion of MWP to fuel is assumed at 85.8%, according to literature that found the designed 100 kg/h plant produces 85.8 kg/h of fuel (Fivga & Dimitriou, 2018).
- The number of operators was estimated by Kodera et al. (2021): three labourers per day on a three-shift schedule for a 200kg/h (6 864 annual hours) plant (shift operators, one shift supervisor for three shifts). The common operators were taken from NREL (Ringer et al., 2006), based on a large-scale oil pyrolysis plant (plant supervisor, plant engineer, maintenance, lab manager/chemist, maintenance, maintenance, maintenance, and maintenance operators, administrator assistant). Refer to Table 3-11.
- The currency conversion is taken as R21.09/₤, refer to Table B-3.

Table 3-11: Literature data for Pyrolysis

Process	MPW pyrolysis	Reference
Capital cost	₤999 492	(Fivga & Dimitriou, 2018
Feed (tpa)	100 kg/hr	
Capacity (tpa)	701.2	
Number of operators	10	
Feed	Mixed Plastic Waste	
Year	2013	
Location	UK	
Product	85.80% Pyrolysis fuel	
	CAPEX Data	
Scale factor n	0.67	Assumption
CEPCI ref	567.3	(Chemengonline, 2020)
Location index	81.2	(WEF, 2019)
CEPCI new	596.2	(Chemengonline, 2020)
Location index new	62.4	(WEF, 2019)

It was assumed that one project manager, lab manager/chemist and secretary are required irrespective of the plant size. At the same time, the number of remaining staff was determined through a linear estimation from reference data. As outlined in section 4.2.3, due to the limited amount of waste processed in Calvinia, the process is run as a batch process in that municipality, while it is a continuous process in GRDM and eThekwini.

Table 3-12: Operators required for pyrolysis (Ringer et al., 2006; Kodera et a.l, 2021)

	Reference	Calvinia	GRDM	eThekwini
Plant supervisor/manager	1	0	1	1
Plant engineer	1	1	1	1
Lab manager/Chemist	1	1	1	1
Maintenance technician	5	1	1	2
Shift operators	3	1	26	36
Administrative assistant	2	1	1	1
Secretary/Receptionist	-	1	1	1

3.5. CAPEX calculations

The capital costs for each treatment option was based on the assumptions represented in section 3.4. These assumptions were used to determine the capital cost required for the assessment year, using Equation 2-9. The working capital was considered as 10% of the fixed capital costs. A 5% contingency factor was applied to the fixed costs. The total capital investment was determined as the sum of fixed cost and working capital.

3.6. OPEX calculations

The OPEX calculations are based on assumptions defined in Table 3-14. Operational expenditure calculations mainly involve raw material (calculated through cost estimation discussed in section 3.3.) and operating labour costs. The number of workers required is specified in the assumptions for each technology option. The salaries for the different workers are given in Table 3-13.

Table 3-13: Salary scales according to the job description (payscale, 2021)

Job description	Salary per employee (R/annum)
Minimum wage workers	62 467.20
Plant manager (chemical)	412 092
Process engineer	386 513
Admin clerk	123 162
Secretary/Receptionist	124 718
Equipment operators (chemical)	128 185

Job description	Salary per employee (R/annum)
Maintenance technician	176 709
Administrative assistant	107 561
Lab manager/chemist	398 095

The TPC relates to the cost of collection, sorting and product production for each treatment option. In addition, the costs of utilities were assumed as a percentage of the TPC, and this should be evaluated during design since different waste management processes may require different utility types and amounts.

Table 3-14: OPEX assumptions for techno-economic assessment (Peters, et al., 2003)

Item	Composting	AD and pyrolysis
	Variable Cost of Production	
Raw Materials	Calculations	Calculations
Miscellaneous Materials	10 % of Maintenance	10 % of Maintenance
Utilities	5% of TPC	5% of TPC
Waste Management	5 % of TPC	5 % of TPC
	Fixed Cost of Production	
Maintenance	3% of FCI	3% of FCI
Major salaries	Calculations	Calculations
Laboratory Costs	10% of Operating Labour	10% of Operating Labour
Supervision	10% of Operating Labour	10% of Operating Labour
Major Salaries	50% of Operating Labour	Calculations
Plant Overheads	50% of Operating Labour	50% of Operating Labour
Capital Charges	10% of FCI	10% of FCI
Insurance	1% of FCI	1% of FCI
local tax	2% of FCI	2% of FCI
	Indirect Production Cost	
Sales Expense	2% of TPC	2% of TPC
General Overheads	2% of TPC	2% of TPC

3.7. Economic analysis

The economic indicators (NPV, IRR and PBP) were calculated based on the amount and price of products. The IRR was computed iteratively and was determined using this automated function in Excel®. The PBP was also calculated using the computerised function in Excel®.

3.8.Sensitivity analysis

The sensitivity analysis determines the uncertainty of the data accuracy used for the different scenarios and the potential influence of parameters. Some variables assessed were landfill credits, sorting costs, recycling and transport costs, and product prices. The different sensitivity scenarios are presented in Table 3-15. The lower bounds of the product prices ranged between 0 to an upper limit value to graphically show the breakeven points more clearly.

Table 3-15: Sensitivity analysis ranges for this study

Parameter		Lower	Base	Upper
Scenario 1	Sorting (R/t)	120	141.8	180
	Transport (%)	-40	0	+40
Waste treatment product price	Scenario 2(a): Compost (R/t)	0	150	500
	Scenario 2(b): Electricity (R/kWh)	0	1.3	12
	Scenario 2(c): Pyrolysis Fuel (R/l)	0	6	24
	Scenario 3: Pyrolysis Fuel (R/l)	0	6	24
Landfill credit	Scenarios 2(a)-(c) and 3 (R/t)	0		1000
Recyclate credit	Scenarios 2(a)-(c) and 3(%)	-40	0	+40

3.9. Summary of Specific Assumptions and Limitations

As identified in chapter 2, the following limitations and gaps were noted during the construction of the methodology:

- Most recent waste characterisations were noted for 2018, 2019, and 2010 for Calvinia, GRDM, and eThekwini. It is noted that eThekwini data is over ten years old, and significant changes to the waste profile may have occurred. However, no recent waste study was conducted within the municipality on specific waste fractions; hence, the 2010 data was used.
- The CAPEX of technologies is based on historical plants for composting. However, no industrial plant data was available for anaerobic digestion and pyrolysis. Therefore, these costs were based on previous investigations for AD and a pilot plant study for pyrolysis. These are deemed suitable for preliminary assessments.
- The exact transportation costs are difficult to estimate. Thus, these costs are based on an assumed transporting distance and costs of a typical truck haul transporting goods for a one-way trip. These costs were based on previous fuel prices, which have drastically increased over the past year. The sensitivity analysis performed on the recyclate prices indicates market fluctuations in the different variables affecting costs (such as fuel or distance).

- The OPEX was assessed using the method detailed in chapter 3.6. Specific mass or energy balances were not included in the costing. However, waste management and utilities are included as a percentage of the total production costs.
- The number and type of workers were based on similar plants of the same nature and were kept consistent with updated salaries suitable for South Africa.
- Recyclate costs were based on 2011/2012 data since it was the most comprehensive data available. These values were escalated using CECPI and PPI values for the years in question. A later comparison between recyclate prices published by PETCO shows minor differences with the assumed prices.
- A full technical feasibility requires the consideration of more factors. However, for this preliminary study, it is assumed that technologies have already been designed considering such factors (i.e. operation and safety). This study does not consider all these factors.

3.10. Impact Assessment

After the technical and economic analysis was completed, an impact assessment was conducted to compare the processing scenarios at a given municipality. For this purpose, six categories were considered: technical, economic, environmental, social, and legislative components. In order to simplify the comparison, the individual categories and their subcategories were assigned ranges (positive, medium and negative effect). Dependent on the category under consideration, green, orange and red stand for a positive, medium or negative effect on the operation.

The impact categories and subcategories are specified as follows, and definitions are presented in Table 3-16:

- Technical: technical feasibility consists of multiple parameters. For this study, only a few parameters were selected as outlined below:
  - Conversion: the amount of waste feed converted to product.
  - Waste processed: The primary requirement is the diversion of waste from landfills. Thus a technology that achieves a high percentage of waste diversion results in a positive effect, while low waste diversion results in a negative effect.
  - The TRL scale of 9 levels characterises the progress in developing a technology, from the idea (level 1) to the full deployment of the product in the marketplace (level 9) (UCT, 2021). For the current work, mature technology will provide a positive effect, while not mature with no commercialised or tested technologies are associated with a negative effect.
- Environmental

  - Emissions: low emissions and pollution will be associated with low risk (positive effect), while high pollution and emissions will be associated with an increased risk (negative effect). GHG Carbon/ GHG emissions: low emissions will be associated with low risk, while high emissions will increase the effect. This is a qualitative category.
- Social impact is considered based on the job creation potential: a low effect will be associated with the lowest number of jobs while the effect will increase with jobs. This category is expressed as the number of jobs per ton waste diverted.
- Legislation: the more legislative requirements pose a greater risk on the technology while the lower risk is associated with the minimum requirements for a waste treatment process. This is a qualitative category.
- Economic
  - Capital Costs: low capital costs will be associated with a positive effect, while high capital costs will decrease the effect. The technologies are compared for the different municipalities using a ratio of CAPEX/t waste or OPEX/ton waste converted.
  - Operational Costs are weighted similarly to Capital Costs.
  - TEA: a positive effect is associated with feasibility and reliability, while non-feasible technology will pose a negative effect.
    - NPV > 0 indicates an economically favourable project
    - IRR > MARR suggests an economically favourable project
    - PBP < Project life is favourable

Table 3-16: Impact table indicating the positive, medium and negative effects on each of the impact parameters of interest

Impact	Sub Impact	Negative	Medium	Positive
Technical	**Conversion**	0-30	31-60	61-100
	Amount of waste diverted from landfill	Diverts little waste	Moderate waste diverted	Diverts most waste
	TRL	TRL 1-3	TRL 4-5	TRL 6-10
Environmental		High	Moderate	Low
Social	**Job creation**	Few jobs	Medium jobs	Most jobs
Legislation		Most	Moderate	Less
Economic	**Capital Costs**	High	Moderate	Low
	Operational Costs	High	Moderate	Low
	TEA	Negative IRR IRR < discount rate PBP > period	Positive NPV IRR < discount rate	Positive NPV Discount Rate lower than IRR

CHAPTER 4: RESULTS AND DISCUSSION

The results from investigating the different technologies for waste treatment in the identified municipalities are presented in this chapter.

4.1. Waste profile

Literature data for Calvinia, Garden Route District Municipality and eThekwini were collated and manipulated to reflect current volumes and compositions. The waste streams were compared based on location. According to Table A-1, the enumeration area was determined based on the population size for each location. It was found that Calvinia was representative of a large village, Garden Route was characterised as a small city, and eThekwini as a metropolitan area, clearly indicating three different area types. The dissertation investigates which waste treatment options are viable in rural/decentralised areas. The assessment of larger communities was done to investigate how the treatment options would perform if situated in other areas with larger waste volumes and different compositions.

The general waste compositions profile, representative of waste available at the landfill, is represented in Figure 4-1 for each location. The principal waste fraction found in all household waste, based on landfill data, irrespective of location, was organics, followed by plastics, paper, and cardboard. This profile is consistent with the country waste profile shown in Figure 2-7. The overall results suggest a distinct difference in waste compositions based on the type of area. For example, there are lower fractions of “organics” and larger “others” fractions in villages (Calvinia) and small cities than metro areas (eThekwini). This may indicate that socioeconomic factors, consumption habits, and possibly education and income are all related to waste generation and could attribute to these differences, as Friedrich and Trois (2010) and Godfrey et al. (2019) highlighted.

In general, the waste hierarchy (as explained in section 0) should be followed, and measures such as reuse and recycling of waste first are considered. However, especially rural and decentralised locations lack reliable waste services and are located far away from recycling facilities. Hence, the integration of waste treatment options in the respective municipality may reduce improperly disposed waste, which is a significant pollution hazard in these areas, while providing economic opportunities.

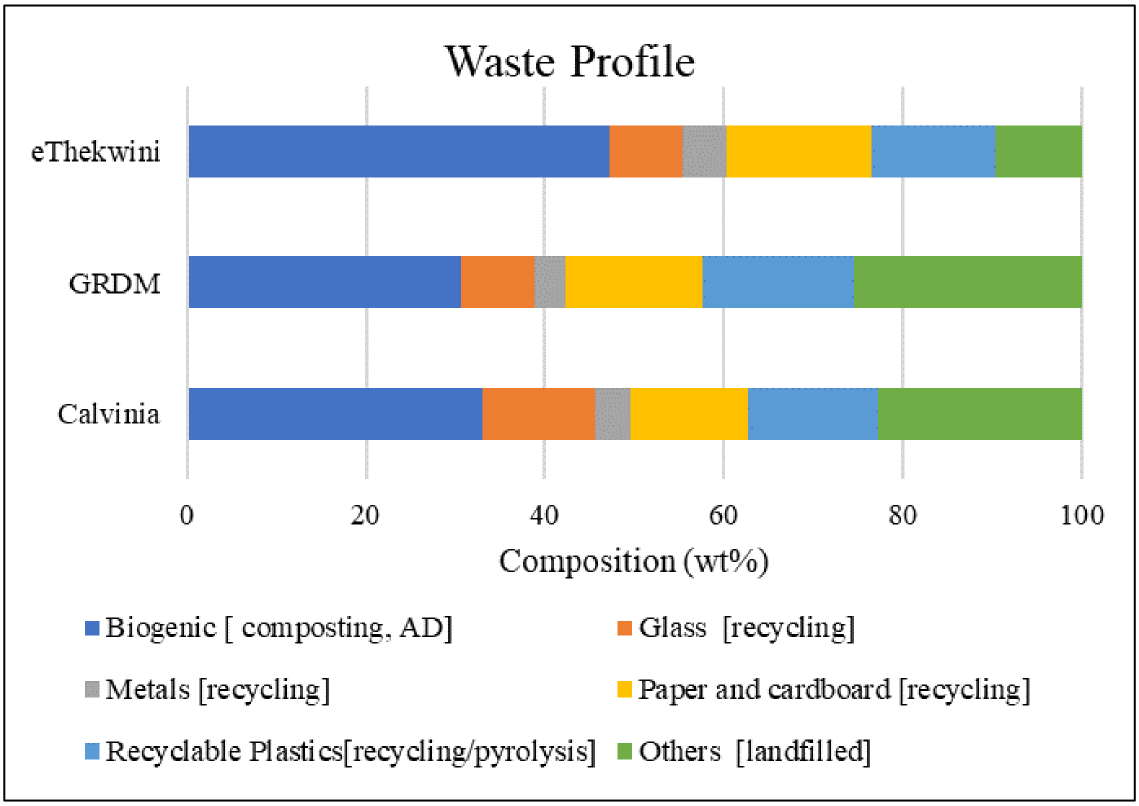


Figure 4-1: Collated waste compositions for each location based on the categories assigned in Table 3-1

4.2.Financial analysis

The order-of-magnitude approach was used to perform a techno-economic assessment on the three different processes under consideration (viz. composting, anaerobic digestion, and pyrolysis) for each location. This approach is considered a preliminary estimate in process design with a ±30 to ±50% uncertainty and is intended to inform waste management technology investigation before in-depth analysis. This type of study is elemental for works such as the Waste-to-Energy Roadmap items of discussion and promotes outcomes of the Waste Research Development and Innovation (RDI).

Four scenarios were evaluated in each case: Firstly, the waste is separated, with an efficiency of 80%. Recyclate is sold to BBCs, and the remaining fractions are forwarded to the landfill (Scenario 1). Secondly, the individual technologies are assessed. The waste is separated, the respective waste fraction is treated, the fractions that can be sold as recyclate are sent to the BBCs, and the remainder is disposed of in the landfill site (Scenario 2(a)-(c)). Thirdly, the individual technologies are reassessed under certain assumptions arising due to reduced waste fraction availability due to the implementation of the EPR (Scenario 3). Fourthly, combinations of technologies are assessed (without considering the impacts of the EPR), where two technologies processing different fractions are combined, the remaining recyclates are being sold, and the remainder forwarded to landfill (Scenario 4(a)-(b)).

4.2.1. Scenario 1: Separation and recycling only analysis

The costs associated with recycling and sorting remain constant throughout the project life (waste volumes are not inflated over the project life). As discussed in section 3.2.1, the costs and revenues of sorting and recycling are distributed between the different product streams. The total costs and credit for sorting and recycling are presented in Table 4-1.

Table 4-1: Total costs and credits for separation and recycling only scenario 1

	Sorting (R/a)	**Landfilling (R/a)**	**Transport recyclate (R/a)**	**Sales recyclate (R/a)**	**Total (R/a)**	**Unit credit (R/t)**
Calvinia	-227 016	330 254	-370 971	271 369	3 637	2.3
GRDM	-12 274 577	17 760 095	-20 527 507	15 259 397	217 408	2.5
eThekwini	-19 792 472	20 059 360	-21 646 791	23 854 682	2 474 778	17.7

The annual total sorting cost is R227 000, R12.3 million and R19.8 million for Calvinia, GRDM and eThekwini. Based on the assumption of 2.6 t/worker, the number of sorters is 2, 106 and 172 workers for the total waste processing of 1 600 tpa, 86 562 tpa and 139 580 tpa for Calvinia, GRDM and eThekwini.

The annual total costs for transporting recyclables is R370 971, R20.5 million and R21.6 million for Calvinia, GRDM and eThekwini. In comparison, the sales of recyclables produce R271 369, R15.3 million and R23.8 million for Calvinia, GRDM and eThekwini. The assessment of the credits in dependence on the available recyclate composition found that Calvinia and GRDM has a higher relative percentage of waste diverted to recyclate sales. In contrast, eThekwini has a higher relative biogenic waste fraction (47% vs 33 and 31 % in Calvinia and GRDM, respectively), translating into higher relative landfilling credits for Calvinia and GRDM, as presented in Figure 4-2. The overall relative recyclate credit is highest in GRDM because of the larger recyclable plastic fraction.

The recyclate was analysed in terms of the ratio of recyclate sales to transport costs, yielding a ratio of 0.73; 0.74 and 1.1 for Calvinia, GRDM and eThekwini, respectively. This means that Calvinia and GRDM fare similarly under the current assumptions, with recycling being sustainable only due to the landfill credits. On the other hand, in eThekwini, recyclate sales and transport costs cancel each other.

Landfill credit is obtained for diverting recyclate, which is R330 254, R17.8 million and R20.1million, respectively. For landfilling, a comparison of recyclables to total waste was examined, yielding 29.5; 28.4 and 27.3% for Calvinia, GRDM and eThekwini, respectively. Although these values are fairly similar, the smaller municipalities accounted for a higher percentage of recyclates. It should also be noted that these amounts were less than the country recyclate content in general waste of 38.3% (described in section 2.1.2)

Based on the total waste, a credit of R2.3 /t of waste was determined for the annual sorting and sales of recyclables. Similarly, the credit for GRDM was R2.5/t of waste. The credit eThekwini was the largest at R17.7/t of waste. The credit per ton of waste processed in each facility indicates that at current assumptions, scenario 1 is feasible and close to break-even in Calvinia, GRDM and eThekwini.

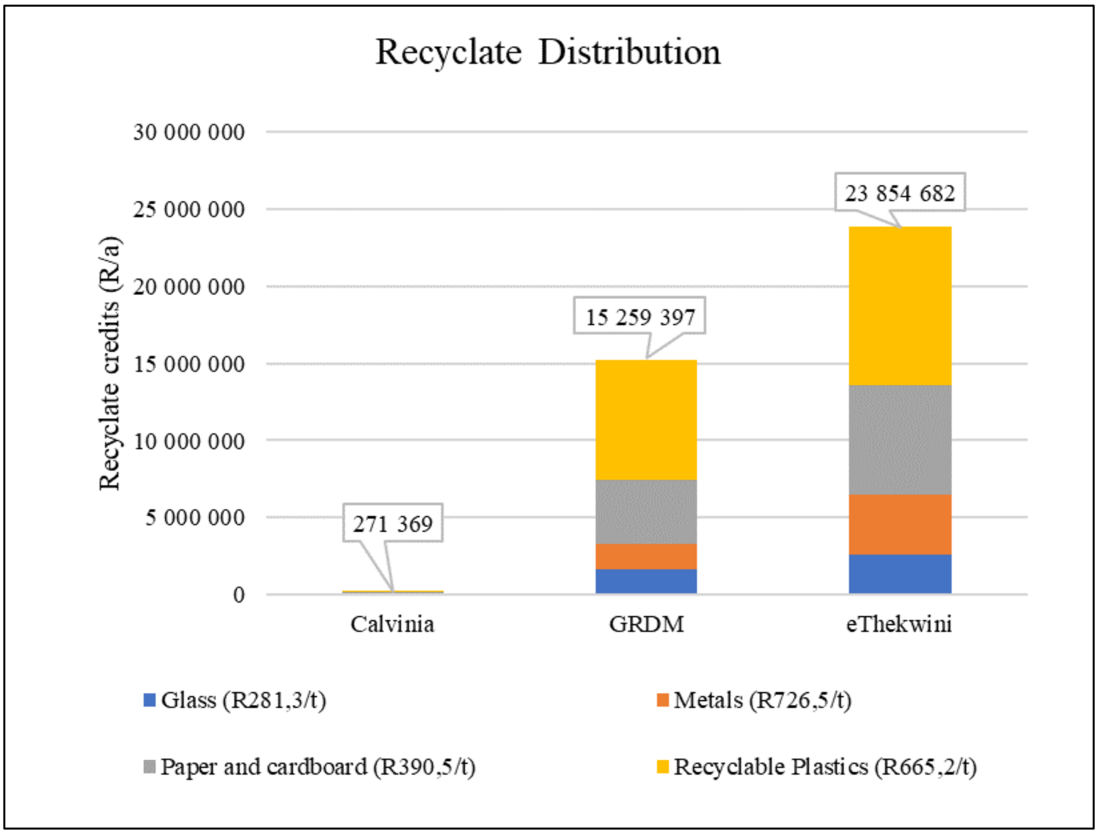


Figure 4-2: Recyclate credit distribution for each location

4.2.3. Scenario 2: Specific Scenarios

The techno economic results for composting, AD and pyrolysis are presented in this section.

Scenario 2(a): Composting

The DAT composting system was investigated for each of the selected municipalities. The feed available at Calvinia is small compared to GRDM and eThekwini. As a rule of thumb, 350 t/month of feed is required to sustain a composting facility as a stand-alone business (Pienaar, 2019). The monthly biogenic material that could be composted was 35 tpm for Calvinia, 1 765 tpm for GRDM and 4 394 tpm for eThekwini. The latter two feed rates are greater than the rule of thumb cut-off estimate, indicating that composting as a stand-alone process should be feasible, but Calvinia was not expected to produce feasible results due to the small feed volumes.

The feedstock cost was calculated as R150 000, R7.3 million, and R11.6 million per annum for Calvinia, GRDM and eThekwini (as explained in Appendix C, Table C-11.). The positive feedstock cost represents a credit towards the OPEX, and this means that the landfill credits for the diversion of feedstock are greater than the costs incurred to sort the stream. Therefore, the feedstock cost is a credit towards the process, represented as a negative on the OPEX calculations.

The scaling factor for the composting process was investigated at an 'n' value of 0.67 and 0.8. Since the capital cost involves mainly the machinery used to develop and maintain the composting area, this value could be closer to one, i.e. that double the size of operation would also require (close to) double the CAPEX expenditure. The scaling factor was therefore investigated in the sensitivity analysis. Based on assumptions and literature data, the TCI ranges from R119 000 (Calvinia), R1.6 million (GRDM) to R3 million (eThekwini) for capacities of 422 to 52 724 tpa of composting waste (n=0.67). The TCI decreases to R63 000, R1.4 million and R3.0 million for Calvinia, GRDM and eThekwini, respectively, for a higher scaling factor (n=0.8). The operational cost was determined as R168/t waste for Calvinia at n=0.67 and R159/t waste at n=0.8. In contrast, the operating costs remain fairly constant for GRDM (R147 and R148/t waste credit) and eThekwini (R116/t waste credit for both) for n=0.67 and n=0.8. It is noteworthy that the operational cost per ton was negative for GRDM and eThekwini, due to the feedstock credit obtained for not landfilling large amounts of biogenic waste, which is higher than the operational costs of composting.

The economic results for the different scaling factor values (n) are presented in Table 4-2. The sale of compost was taken at R150/t due to the fluctuating fertiliser prices, the lower limit from literature (R150 to R350 (Jagnath, 2010)). The NPV is negative for both n values in Calvinia, indicating that the process is not feasible. On the other hand, the NPV is very similar for both n values for GRDM and eThekwini, with an NPV greater than zero. The positive NPV indicates that the investment is feasible over the project life at the given assumptions. Furthermore, the IRR is higher than the discount rate of 20% and results in a PBP of one year (GRDM and eThekwini). This indicates that the project will recover from the investment during the first year, meaning that composting is a highly financially beneficial investment.

Table 4-2: Techno-economic results for composting for n=0.67 and n=0.8

	n=0.67			n=0.8		
	Calvinia	**GRDM**	**eThekwini**	**Calvinia**	**GRDM**	**eThekwini**
NPV (ZAR)	-355 384	44 222 572	89 953 679	-259 457	44 582 535	90 239 496
IRR (%)	-8.6	272.6	227.5	-3.6	311.5	239.1
PBP (a)	>15	1	1	>15	1	1

Since composting does not require skilled workers, operational labour requires minimum wage workers, while the supervisory and major salaries were taken as a percentage of the total operation salary. The number of workers needed is 2, 4 and 8 for the three municipalities based on assumptions.

Scaling Factor (n)

Since the scaling factor was unknown for composting and no literature value was found, the scaling factor's effects on the NPV were investigated, as shown in Figure 4-3. The initial scaling factor of 0.67 is usually used by industry convention, while a factor of one indicates numbering up rather than scaling up costs. The NPV is below zero irrespective of the scaling factor (0 to 1) for Calvinia, implying that the OPEX is too high to provide feasible results. On the other hand, the NPV is positive for all scaling factors for GRDM and eThekwini.

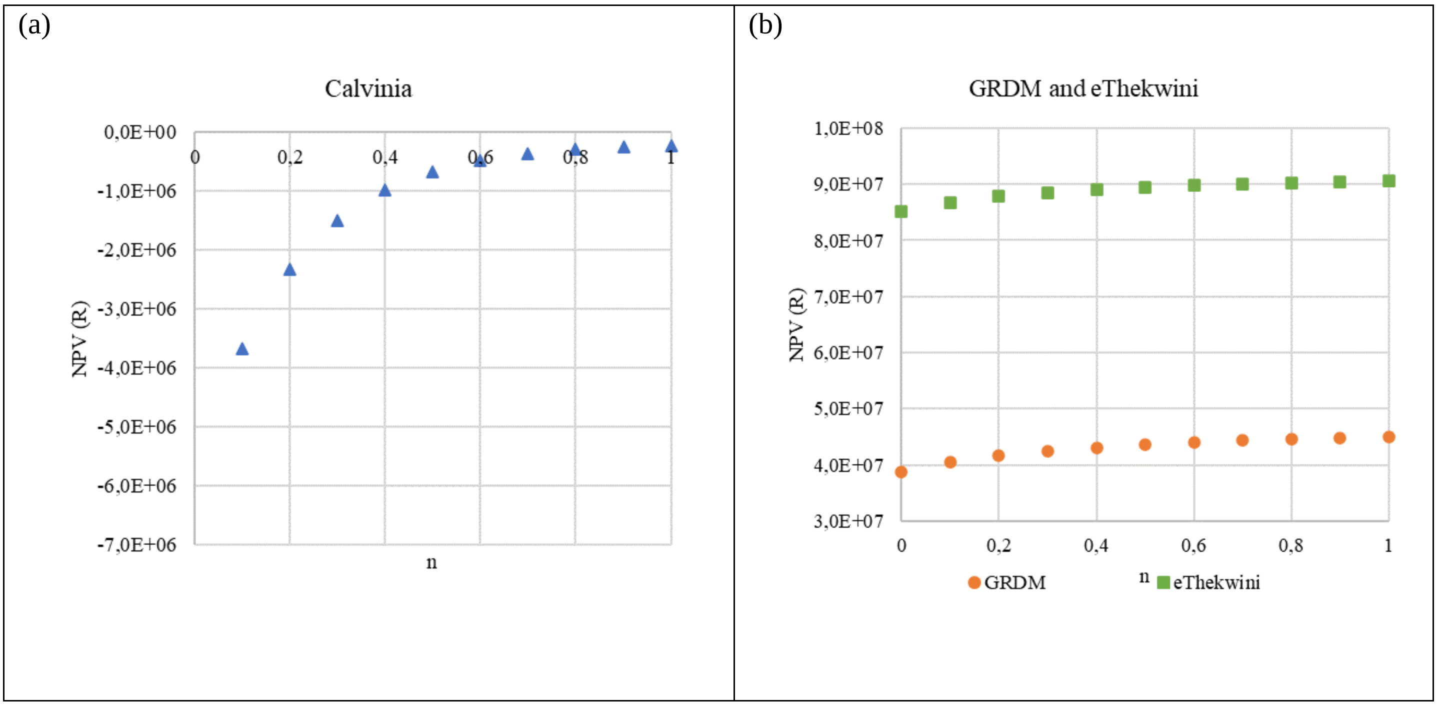


Figure 4-3: Effects of the scaling factor (n) on the NPV for composting in (a) Calvinia and (b) GRDM and eThekwini

Amount of waste

The amount of waste was investigated for each location, considering the local waste composition and CAPEX and OPEX costs. The amount of waste available affects the feedstock cost and recyclate revenue through feedstock allocation, the amount of product produced, and the amount of the total feed sent to landfill within the first three years. Additionally, it also affects the scale of the plant. As presented in Figure 4-4, the NPV increases with increased waste volume for all locations. Calvinia and eThekwini behave similarly with a minimum volume of waste of at least 2 600 tpa and 2 800 tpa, respectively, for the break-even of the processes. However, GRDM requires a higher amount of waste of at least 3 400 tpa. This indicates that the location based composition of waste plays a significant role in the feasibility of the process.

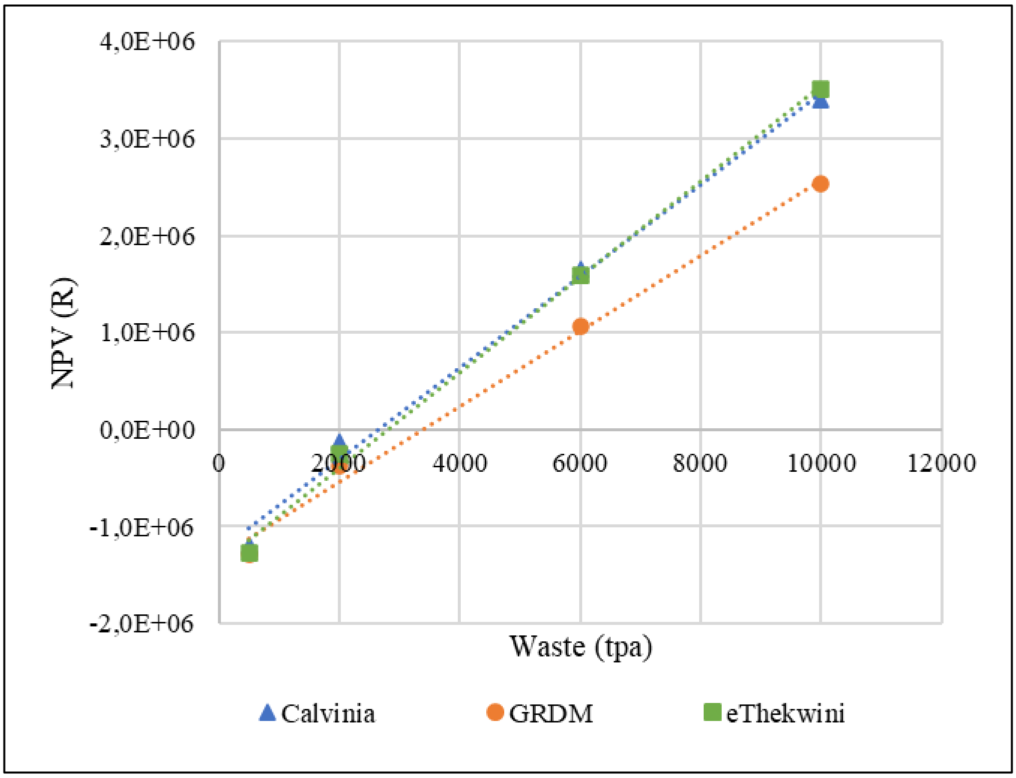


Figure 4-4: Sensitivity analysis on the amount of waste on the NPV for composting (n=0.67)

Scenario 2(b): Anaerobic Digestion (AD)

The feedstock cost allocation for AD was the same as composting given in Table C-11. The unprocessed organic waste was sent to landfill at a cost within the first three years until maximum capacity was reached. All biogas was assumed to be converted to electricity and sold at R1.3/kWh. A 35% energy conversion to electricity was considered. According to literature, economically sustainable AD requires 100 tpd and will cost about R125 million to build (Pienaar, 2019). The feed throughput is approximately 1.3 tpd for Calvinia, 67.7 tpd for GRDM and 168.1 tpd for eThekwini, indicating that AD should be feasible for eThekwini only.

The financial indicators for the AD system exhibit poor economic feasibility in Calvinia, as seen in Table 4-3. The NPV is negative for Calvinia (-R33 million) but positive with R14.5 million and R208.7 million for GRDM and eThekwini, and payback periods of >15, 5 and 4 years, respectively (Table 3-3). These results are in line with the literature, where in a case study performed by Gogela (2017), a small-scale, commercial biogas system was found to not be financially viable in South Africa.

The TCI range between R16 million (Calvinia) and R242 million (eThekwini). The high initial investment costs are a key economic characteristic of anaerobic digestion (Amigun & Von Blottnitz, 2010). It should be noted that a low operational expenditure relative to CAPEX has been reported for AD processes, with about 4–7.5% of the capital cost for a farm-scale plant (Von Blottnitz, 2016). The operational to capital cost percentage ranges between 13% (eThekwini) and 29% (Calvinia) in this current study are comparatively higher than the literature percentage. This deviation can be attributed to differences in waste compositions and resulting differences in expense and revenue streams in the cost allocations compared to the literature.

Table 4-3: Techno-economic results for AD using Tsilemou et al. (2006) (adapted from Rapport 2015)

	Calvinia	**GRDM**	**eThekwini**
NPV (ZAR)	-33 082 705	14 460 739	208 658 236
IRR(%)	n/a	22.4	35.0
PBP (a)	>15	5	4

Furthermore, given that not all households have access to electricity in many parts of the country (as described in section 2.1.1), AD provides a possible alternative in these locations, especially those far away from national grid lines.

Scaling Factor (n)

As discussed above, a scaling factor of 0.5581 was used in this assessment. However, according to Amigun and Von Blottnitz (2010), who conducted a capacity-cost and location-cost analysis for biogas plants in Africa, the use of the “correct” value for n is critical for biogas processes. They found that the cost capacity factor (referred to as the scaling factor) obtained during their study was notably greater than the widely used 0.6-factor rule. The scale factor for small-scale (family) to medium biogas plants was 1.21, while institutional to large-scale biogas technology had a scaling factor of 0.80, indicating economies of scale and a decrease in the marginal cost of investment as plant capacity (output) is increased (Amigun & Von Blottnitz, 2010).

For this reason, the effects of the scaling factor (n) on the NPV was investigated, as given in Figure 4-5. The scaling factor was examined at a reference capacity of 30 000 tpa of feed for each location. The results indicate that the NPV behaves similarly in Calvinia and GRDM for the reference functions from Tsilemou. In Calvinia, an increase in the n value increases the NPV to more positive values but remains negative. The eThekwini scenario displays an opposite trend where an increase in scaling factor(n) values decreases the NPV to lower values.

In Calvinia, the NPV is less than zero irrespective of the scaling factor (0 to 1.2), implying that the OPEX is too high to provide feasible results. AD was further investigated at a small scale (Calvinia) by using the assumption of n=1.21 (the scaling factor for a small to medium process according to Amigun and Von Blottnitz (2010)). At a scaling factor of 1.21, the TCP decreases to R896 000 (from R2 143 000 (n=0.67). A TCP of at least R430 000 is needed to make the process feasible (n=1.21), at which the NPV is R6 217, IRR is 20.15%, and PBP is seven years. That is a TCP of about 46% of the capital investment at a scaling factor of 1.21.

It should be noted that the capital and operational costs that affect the NPV are linked to the recycling, sorting and treatment process. Therefore, based on cost allocation, as the amount of feed increases (with capacity increases), due to the much smaller amounts of organics in Clavinia, AD units are still minimal compared to GRDM and eThekwini. In this case, Calvinia can overcome the costs associated with this. However, in the case of GRDM and eThekwini, where there are much more organics (resulting in much larger AD facilities), the revenue does not cover the capital and operational expenses of recycling and processing.

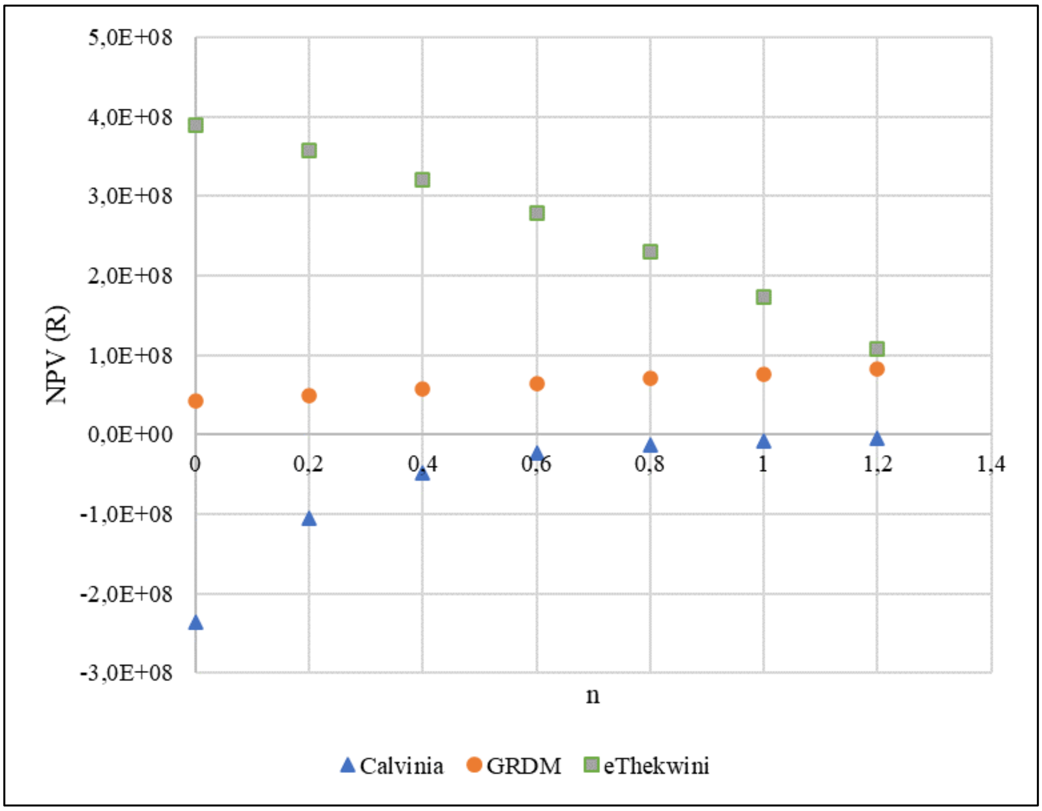


Figure 4-5: Sensitivity analysis of scaling factor on NPV for AD

Scenario 2(c): Pyrolysis

The thermal decomposition of Mixed Plastic Waste (MPW) polymers yields oils with excellent qualities, which can be used as a liquid fuel and a chemical source (Czajczyńska, et al., 2017). Although pyrolysis can be manipulated to provide a wide range of product compositions of solid, liquid and gas in different ratios, this study investigated the liquid product of pyrolysis. The reference found that the 100 kg/h plant produced 85.8 kg/h of fuel. Using the characterisation discussed by Lin (2018), the available plastics in Calvinia is only 0.6 tpd which is much less than 10 tpd for a usual batch waste to oil process. Thus, the process in Calvinia should be a batch process. The GRDM has a daily available plastic waste amount of approximately 40 tpd and 53 tpa for eThekwini, indicating that these processes should be fully continuous (greater than the 30 tpd capacity described by Lin (2018)). Based on these assumptions, the number of operational workers was divided between one shift for batch processes and three shifts for continuous operations. The pyrolysis fuel price was R6/l since the refining level was not mentioned. The pyrolysis process can utilise the non-recyclable plastic fractions, which was combined with the 'others' fraction and sent to landfills in the other scenarios. The first three years have an operational capacity of 70%, 80% and 90%, which means a leftover of unprocessed plastic of 30%, 20% and 10% of plastics. Within the first three years, the unprocessed stream was assumed to join the recyclate stream and proceeds to BBCs for sales instead of landfilling, serving as an income stream in these years. The economic results are provided in Table 4-4. The conventional scaling factor of 0.67 was used to complete CAPEX calculations.

As discussed in chapter 2.5.3, the pyrolysis system examined in this study converts plastic waste to a heavy fuel substitute or a petrochemical feedstock. The process can use recycled non-condensable gases to provide heat to the system. Thus, the fuel produced can be sold much cheaper than conventional fuel.

The TCI ranges between R10.8 million (Calvinia) to R189.6 million (eThekwini), for a capacity of 287 and 19 328 tpa plastic. Based on the conversion of 85.8%, the total fuel produced is 209 tpa, 10 051 tpa and 14 096 tpa for Calvinia, GRDM and eThekwini, respectively. The density of pyrolysis fuel ranges between 0.6668 and 0.740 kg/l. Using the latter density value, the fuel produced in litres is 282 723, 13 582 748 and 19 048 418 litres for Calvinia, GRDM and eThekwini. The OPEX is approximately R3 million, R30 million and R43 million annually for Calvinia, GRDM and eThekwini, respectively. The major OPEX expenses result from the fixed production costs. The total number of workers is 8, 33 and 47 for Calvinia, GRDM and eThekwini.

Based on the cost allocation, the feedstock cost was determined as a credit of R54 000, R2 million and R169 000 for Calvinia, GRDM and eThekwini (refer to C-12). The NPV for Calvinia is -R17 million, indicating that the pyrolysis of plastics is not economically feasible. The NPV is R34.6 million in GRDM with an IRR of 24%, meaning that both key financial indicators are favourable. Similarly, data for eThekwini results in a positive NPV of R67.6 million with an IRR of 27%. The cost of production is R5 256, R1 000, R898/ t waste diverted. Although GRDM exhibits higher production costs, the process is feasible in GRDM, possibly due to the larger recyclate sales income, which is higher by a factor of 100 and 2 than Calvinia and eThekwini, respectively.

Table 4-4: Techno-economic results for pyrolysis of plastic waste

	Calvinia	**GRDM**	**eThekwini**
NPV (ZAR)	-16 671 129	34 636 764	67 637 429
IRR(%)	n/a	24.4	26.5
PBP (a)	>15	5	5

1.2.4. Scenario 3: Implementing EPR in collection rates

The advancement in legislation such as the EPR targets is expected to change the waste management landscape, and the TEA model was applied to forecast the effects of such changes. The EPR targets ensure that a certain amount of material is recycled by law. Since all recyclables were assumed to be sold at BBCs, the only scenario affected by the EPR regulations is the pyrolysis process (scenario 2(c)), ensuring that the required fraction of the process stream (plastic) is recycled instead of processed.

As shown in Figure 4-6, a distinct trend was noticed for the change in feed due to the implementation of the EPR targets. The targets essentially decrease the amount of plastic available for pyrolysis drastically between years three and four (where the EPR targets were assumed to be first implemented). Since these are national targets, they are the same for all locations resulting in a proportional decrease in each location, as noticed in Figure 4-6. During years one to three, the plant operates at a capacity of 70%, 80% and 90%; this means that there is a leftover of 10%, 20% and 30% of plastics that were not processed by pyrolysis. The unprocessed stream was assumed to join the recyclate stream and proceed to BBC for sales instead of the landfill, serving as an income stream in these years.

The TCI and OPEX are based on the available feedstock at year one and thus assume a higher plant capacity than required once the targets are implemented. It is possible to initially design the plant at a lower capacity to account for the diminishing process feed stream in the future. The revenue from feedstock cost and recyclate revenues decreased through cost allocation following the decrease in available feedstock.

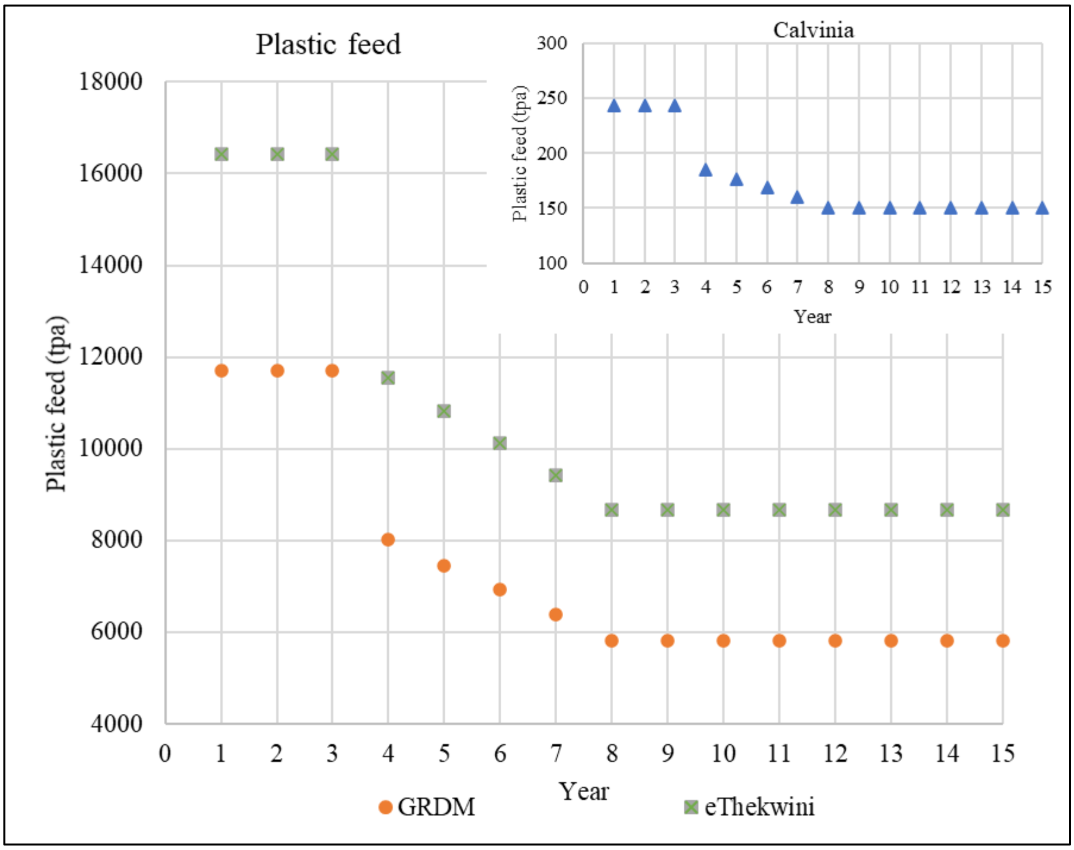


Figure 4-6: Effects of EPR on plastic feed rate on the pyrolysis process

Under the current assumptions, the overall economic results are presented in Table 4-5. The NPV is less than zero (-R17.2 to -R45.8 million) at all locations, with the worst performance in Calvinia, indicating that the project is not feasible to investors at current assumptions. However, IRRs of 10.4% and 17.73% for GRDM and eThekwini, suggest that the project becomes feasible in these locations at that lower discount rate. The PBP is often set as a limit value related to the economic life of the investment, e.g., a PBP shorter than half the economic life (Yard, 2000). In this case, a PBP of 6-7 years is about half the economic life of 15 years, hence, still providing an attractive option. It should also be noted that as the selling price of product fuel increases, the PBP decreases, resulting in a more attractive scenario.

Table 4-5: Economic results for the implementation of EPR on plastic pyrolysis

	Calvinia	**GRDM**	**eThekwini**
NPV (ZAR)	-17 248 380	-45 788 338	-15 868 361
IRR (%)	n/a	10.35	17.73
PBP (a)	>15	7	6

Although results indicate that pyrolysis is not feasible with EPR implications, and the EPR may be perceived as a threat to the process feed, the overall scenario can overcome the loss from pyrolysis fuel revenues by finding alternative feed sources such as non-recyclable plastics or urban mining from landfills. Furthermore, price increases are possible with the functioning fuel market and could promote alternative fuel sources at a lower cost.

However, it should be noted that at current assumptions, the EPR targets for waste streams (such as paper, metal and glass) are already met in year one since 100% of these streams were assumed recycled. However, it must be noted that this assumption overestimates the recyclable contents, all available recyclable materials (glass, metal, paper and cardboard) were forwarded to the BBCs for recycling. In reality, only a fraction might be recycled. As noted by the GRDM, some recyclable content is assumed to be contaminated by organics in waste (Eden District Municipality, 2016a-e; Garden Route District Municipality, 2019).

1.2.5. Scenario 4: Combined scenarios

Two combined scenarios were investigated (a) the combination of composting and pyrolysis and (b) the combination of AD and pyrolysis.

Scenario 4(a): Composting and pyrolysis

The CAPEX calculations combined the FCI and TCI from the individual processes in section 4.2.3 to provide the overall capital costs. For both processes, a scaling factor of n =0.67 was used. The combined CAPEX of R10.9 million, R146 million and R192.7 million are found for Calvinia, GRDM and eThekwini, respectively, and used to complete the OPEX and DCF analysis. The bulk of the capital cost stems from the pyrolysis units since composting has an overall low capital investment (1-2% of the total combined). The OPEX ranges from R3.5 (Calvinia) million to R27.6 (eThekwini) million per annum. The results are presented in Table 4-6.

Table 4-6: CAPEX and OPEX results for composting and pyrolysis

	Calvinia	GRDM	eThekwini
TCI Composting	119 248	1 642 597	3 026 643
TCI Pyrolysis	10 788 059	144 358 381	181 072 115
TCI Combined	**10 907 307**	**146 000 978**	**192 655 978**
TPC	**3 493 169**	**20 836 222**	**27 561 877**

The cost allocation determines the feedstock cost by considering both processes, calculated at approximately R236 000, R11 and R15 million for Calvinia, GRDM and eThekwini. And the recyclate revenue is R47 000, R1 and R6 million for Calvinia, GRDM and eThekwini. The key economic parameters for the combined process are presented in Table 4-7. The combined scenario is not feasible in Calvinia. However, the NPV is R78.8 and R153 million for GRDM and eThekwini. The project displayed favourable economic characteristics for these locations with an IRR greater than the discount rate and PBP of four years.

Table 4-7: Techno-economic results for combined composting and pyrolysis(Scenario 4(a))

	Calvinia	**GRDM**	**eThekwini**
NPV (ZAR)	-18 884 744	78 780 066	152 958 710
IRR(%)	n/a	29.6	33.8
PBP (a)	>15	4	4

Comparison to stand-alone processes found that:

- Similar to the stand-alone processes (composting and pyrolysis), the process (scenario 4(a)) was not feasible in Calvinia.
- The combined scenario (scenario 4(a)) is less attractive than composting (scenario 2(a)), with lower NPVs and higher PPBs in GRDM and eThekwini.
- The combined scenario (scenario 4(a)) is more feasible than the standalone pyrolysis process (scenario 2(c)) with greater NPVs and lower PBPs (by one year) in GRDM and eThekwini (base of 5 years).

Scenario 4(b): AD and Pyrolysis

The combined CAPEX for AD and pyrolysis is R27 million, R290 million and R432 million. The bulk of the capital cost results from the AD units for Calvinia and eThekwini (about 60%) for the combined scenario, while the AD system cost is lower in GRDM (50%). The OPEX is R8.2, R43.2 and R70.4 million per annum for each location. The results are presented in Table 4-8. The feedstock costs and recyclate revenue are the same as the combined scenario of composting and pyrolysis discussed above.

Table 4-8: CAPEX and OPEX results of combined AD and pyrolysis process

	Calvinia	**GRDM**	**eThekwini**
TCI AD	16 353 986	145 365 249	241 931 794
TCI Pyrolysis	10 788 059	144 358 381	189 629 335
TCI Combined	**27 142 044**	**289 723 630**	**431 561 128**
TPC	**8 199 977**	**43 180 800**	**70 408 313**

The key economic parameters for the combined process is presented in Table 4-9. The combined scenario was not feasible in Calvinia. However, the NPV is R48.6 million in GRDM and R270.3 million in eThekwini. The project displays favourable economic characteristics for these locations with an IRR greater than the discount rate and PBP of five and four years, respectively.

Table 4-9: Techno-economic results for the combined scenario of AD and pyrolysis

	Calvinia	**GRDM**	**eThekwini**
NPV (ZAR)	-47 622 734	48 611 064	270 301 744
IRR	n/a	23.14%	31.16%
PBP (a)	>15	5	4

Comparison to stand-alone processes shows that:

- In GRDM, pyrolysis with composting is more favourable, while in eThekwini, pyrolysis and AD are more economically favourable. Higher revenue from biogas production could be higher than compost sales in eThekwini, which has a higher biogenic waste fraction.

4.2.2. Summary

A graphical summary of the NPV for each scenario for each location is presented in Figure 4-7. The increase of plant size was noticed to increase the NPV for all scenarios, except scenario 2(c), where the NPV was higher than GRDM (although still negative). Except for scenario 2(c), all scenarios are feasible in GRDM and eThekwini. For Calvinia, scenarios 2(c), 3 and 4(a) produced higher NPVs, although not feasible, implying that small changes to specific parameters could make these scenarios more feasible. Of the positive results, according to the NPV, scenario 4(a) is most favourable in GRDM and scenario 4(b) was most favourable in eThekwini.

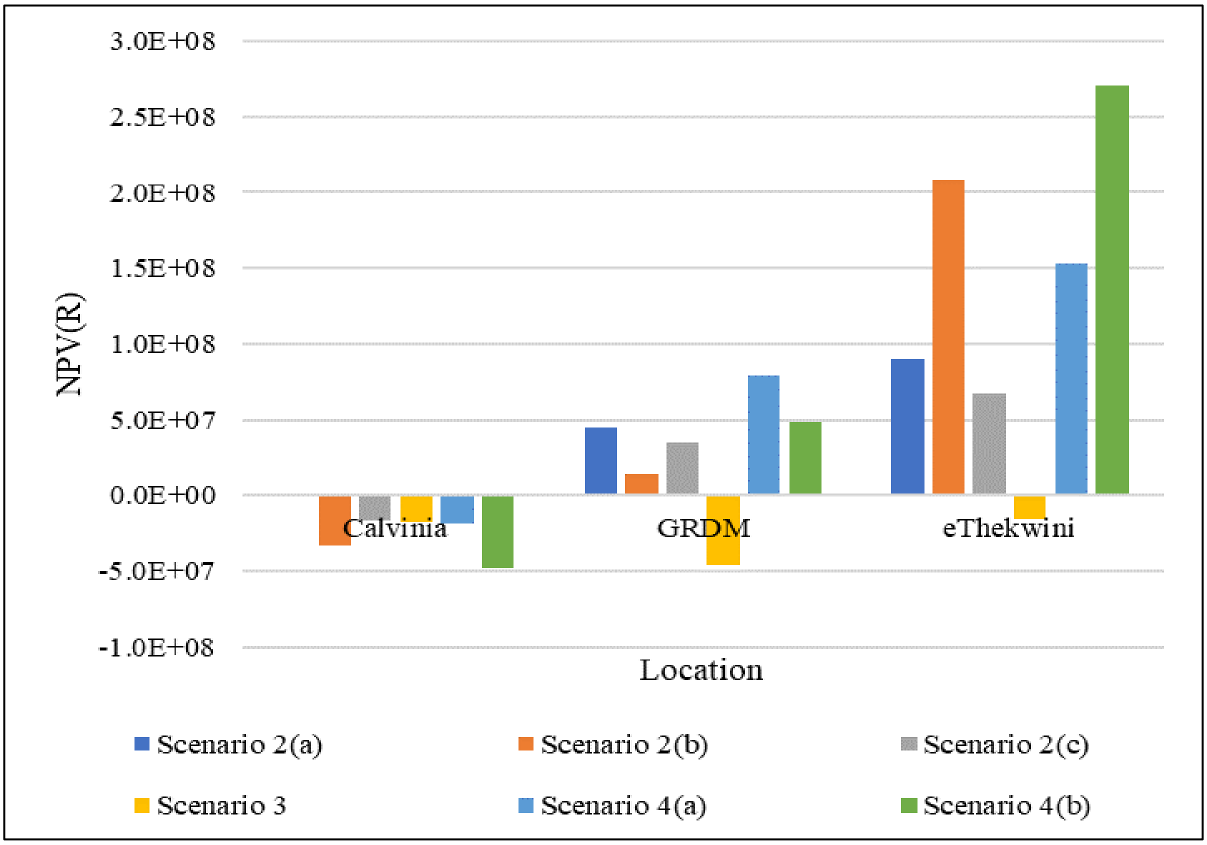


Figure 4-7: Graphical summary of NPV for all scenarios

Implementing simple separation and recycling are best suited for all municipalities irrespective of scale. In smaller, decentralised municipalities, manual sorting could create more job opportunities and reduce separation costs, further promoting the scenario. AD requires more feed to become economically viable, although recyclate revenue plays a role in feasibility. It is recommended that larger municipalities with constant feedstock consider the uptake of AD technologies. Alternatively, combining multiple smaller municipalities to increase feedstock could render valuable energy sources to decentralised localities. Pyrolysis fuel could aid in supplying local heavy petroleum fuel and is best suited for larger municipalities with a stable feed of plastics. Scenario combinations fare better at larger scales, while within smaller municipalities, single treatment options may provide higher NPVs.

4.3. Sensitivity analysis

The different parameter effects were investigated through a sensitivity analysis as described in section 3.8 based on the ranges specified in Table 3-15. This section presents the results for the different scenarios.

4.3.1. Separation and recycling only: Scenario 1

The sorting and transport costs were investigated through sensitivity analysis for the separation only case. The trends were expected to be similar since the assumptions were constant for all processes.

<u>Sorting</u>

The sorting costs were investigated between R120 and R180/t of waste. The EPR and CEPCI derived values (discussed in section 3.1.1) were lower than R120/t. Since feasible results were found at R120/t, the scenario is expected to be feasible at lower prices (CECPI and EPR values). The general trend showed that as sorting costs increased, the overall revenue decreased, and at a certain sorting price, the plant began not to be feasible (refer to Figure 4-8). The breakeven sorting cost for each municipality was determined (at what sorting cost the total credit/cost became zero). Calvinia and GRDM performed similarly, allowing for a cost of separation of up to R144.31/t and R144.15/t of waste. These values are only marginally higher than the base value: 141.8 R/t. At eThekwini, a higher value of up to 159.54 R/t could be afforded for the scenario. The assumption of the same cost for sorting (R/t) for all municipalities means that scaling cannot affect the economics. However, a lower transport cost may allow higher sorting costs to break even.

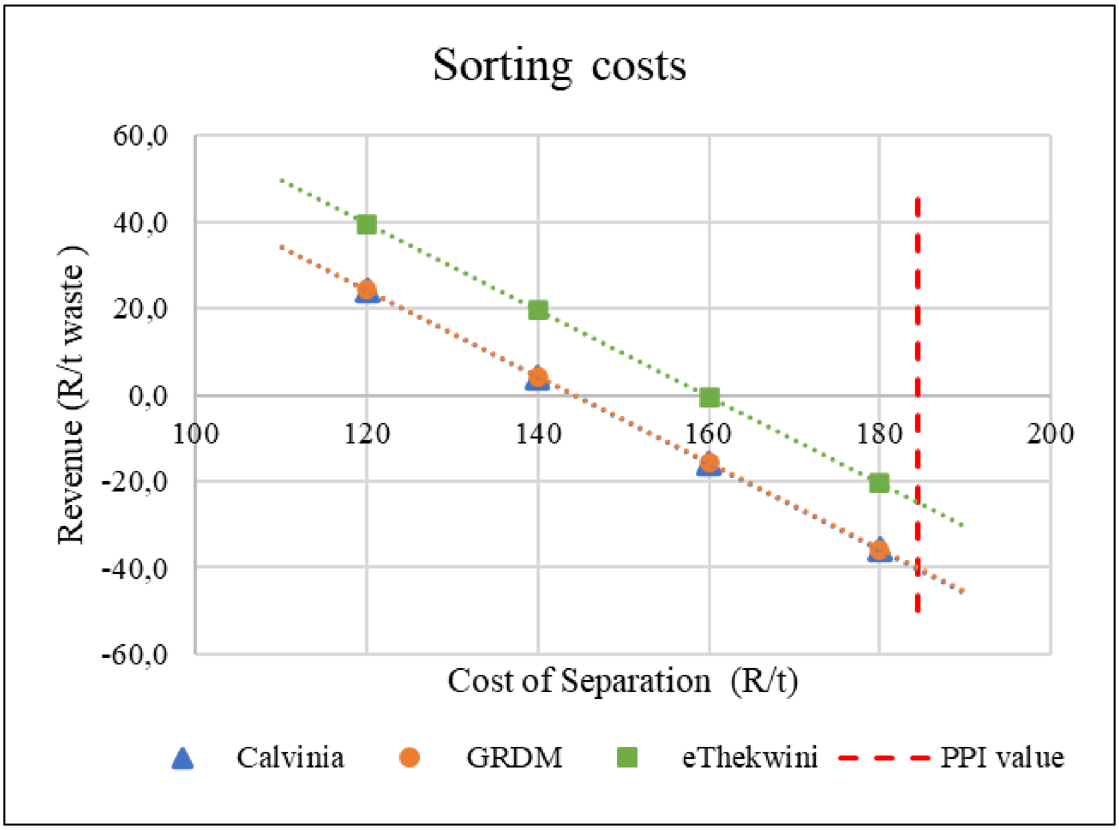


Figure 4-8: Sensitivity analysis of the effects of the separation cost to revenue for scenario (1)

Transport of recyclables

The distance between each municipality's collection and dumping sites does not change. However, with the increased emphasis on waste treatment and recycling, more recycling and buy-back centres are expected to be established. In other cases, with the current harsh economic conditions of South Africa, other centres may close, resulting in greater distances. Another influencing factor is the fluctuating fuel cost in the country. Therefore, any of these factors could influence transportation costs, thus considered through a varying approach of a 40% increase or decrease in costs.

The transport costs were assessed in each municipality, where all other aspects remained as per the initial assumptions. In the base case, the transport cost per ton of recyclate was highest for GRDM (150 km at 4.5 R/km/t) and lowest for eThekwini (100 km at 4.5 R/km/t). Calvinia was assessed with 400 km at 1.64 R/km/t. The change of transporting costs on the overall sorting costs or credits was investigated in Figure 4-9. All locations were sensitive to a change in the cost of transporting recycling, with a general trend indicating that an increase of transport costs per ton of waste decreased the credits received. From the graph, it can be deduced that Calvinia and GRDM cannot afford a higher transporting cost, while eThekwini can sustain an increase of about 11.2% of the current cost.

The breakeven point for each case was determined. The two factors that affect the cost of transporting recyclables are the distance travelled in km and the unit cost of transporting a ton of waste. The transport cost could be increased in Calvinia to R1.65/t/km (400 km) or 404.1 km (at R1.64/t/km), at which the project will break even. In GRDM, the unit transport cost needs to decrease to R3.36/t/km (at 150km) or a distance of 121.7 km (at R4.50/t/km) to break even. eThekwini has a similar trend to Calvinia, where the unit cost could be increased to R5.01/t/km (at 100km) or a distance of 111.5 km (at R4.50/t/km) to reach the break even point.

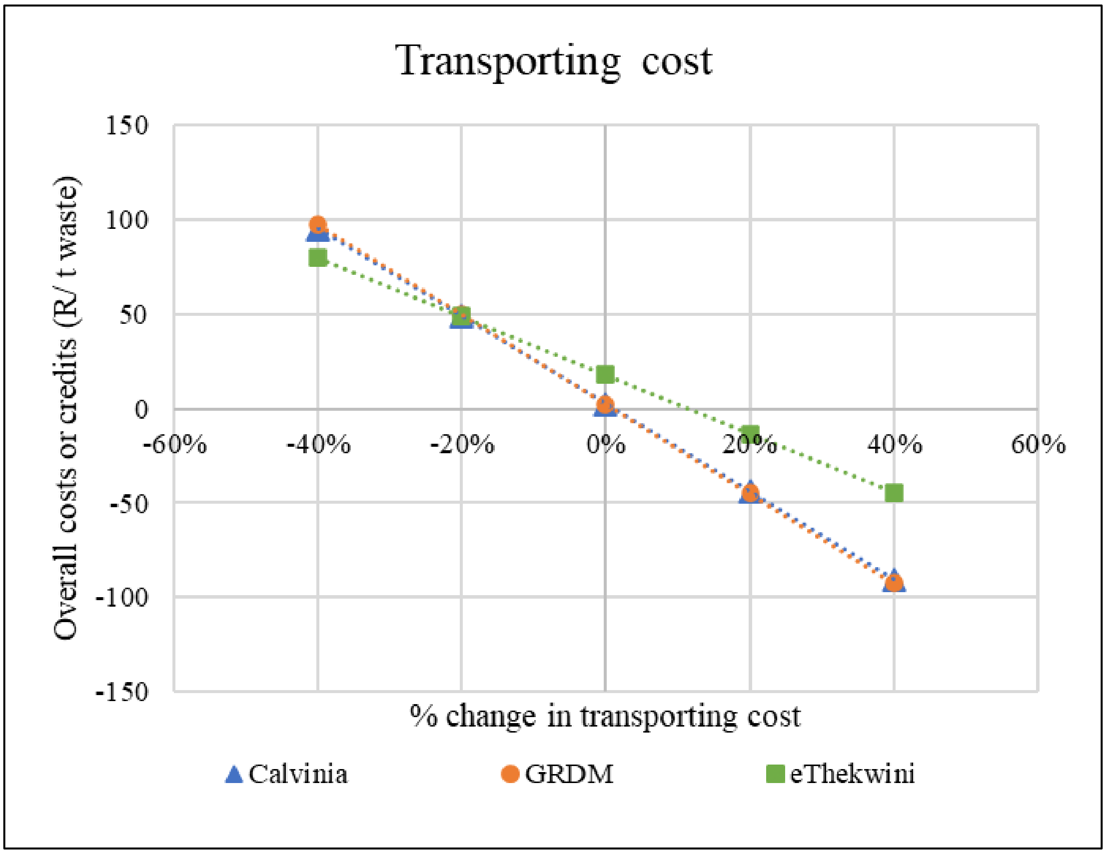


Figure 4-9: Sensitivity analysis of transporting costs on scenario 1 for each location

4.3.2. Waste treatment product price

The product prices for each waste processing scenario were investigated, keeping all other assumptions constant.

<u>Scenario 2(a): Composting: Compost price</u>

The feasibility of composting relies on international prices (SA is a price taker), and exchange rates are expected to influence the market price of compost (Gogela, et al., 2017). The minimum price of compost for an NPV of zero was investigated. For GRDM and eThekwini, a negative price was calculated, indicating that the process is feasible even without sale revenues from compost. The process will still be viable at a negative price of compost per ton of R623 and R482 for GRDM and eThekwini, respectively. This compost can be sold to nearby agricultural facilities to improve soil nutrient levels at a much lower price in GRDM and eThekwini, promoting the local communities.

A sensitivity analysis was conducted on the price of compost on the NPV for Calvinia only to determine the breakeven points. From Figure 4-10 (a), an increase in compost price increased the NPV. The process was not feasible in Calvinia for compost prices lower than R462/t for a scaling factor of 0.67 and R383/t for a scaling factor of 0.8. This trend indicates that under the assumption of this study, at a (high) landfill credit of R584, the increase of compost price above the upper literature value will make the process viable in Calvinia.

Scenario 2(b): AD: Electricity price

Electricity was considered the main product of the AD process. The price of electricity in South Africa is guided by NERSA who has recently motivated tariffs based on cost-to-serve, resulting in Eskom developing a restructuring plan. This means that economic drivers such as consumer needs, competition, smart working, technology, green economy, efficiency and recovery costs will be considered in proposed charges (Pricing Department, 2020), resulting in tariff changes over the coming years. Therefore, the influence of different electricity prices was investigated in Figure 4-10 (b).

The increase in the price of electricity positively influenced the NPV of AD for all locations. The breakeven cost was determined as R9.8/kWh in Calvinia. Due to the low organic feed available in Calvinia, high electricity tarrifs are required to overcome the OPEX and high capital investments. However, the higher feed volumes and thus product volumes in GRDM and eThekwini resulted in lower electricity prices to break even than the base value (1.3 R/kWh) at R0.9/kWh and R0.6/kWh, respectively.

Scenario 2(c): Pyrolysis fuel price

The key benefits of pyrolysis fuel are the diversion of waste from landfills and the production of a cheap fuel product that the local community may use. An analysis was conducted on the fuel price while holding all other variables constant. The minimum price the fuel would have to fetch in Calvina is R20.9/l, while the price decreases from the base value of R6/l to R5.3/l for GRDM and R5.0/l in eThekwini. Lower fuel prices are possible in GRDM due to the higher pyrolysis feed fractions (higher plastic compositions) than for Calvinia and eThekwini. See Figure 4-11 (a). The pyrolysis system examined in this study converts plastic waste to a heavy fuel substitute or a petrochemical feedstock.

Scenario 3: Pyrolysis fuel price for EPR

The fuel price trend was similar to the pyrolysis fuel scenario 2(c). However, higher prices were required to break even to compensate for the decrease in process feed which was diverted to recycling due to the EPR targets. Although recycling creates a revenue stream, transport costs play a significant role in the receiving revenue. The minimum fuel prices were determined at R26/l (333% increase), R7.3/l (22% increase) and R6.3/l (5% increase) for Calvinia, GRDM and eThekwini (from the base case of R6/l), refer to Figure 4-11 (b). A slight increase in fuel price will result in feasibility in GRDM and eThekwini, which is possible with the country's constant variation in fuel prices.

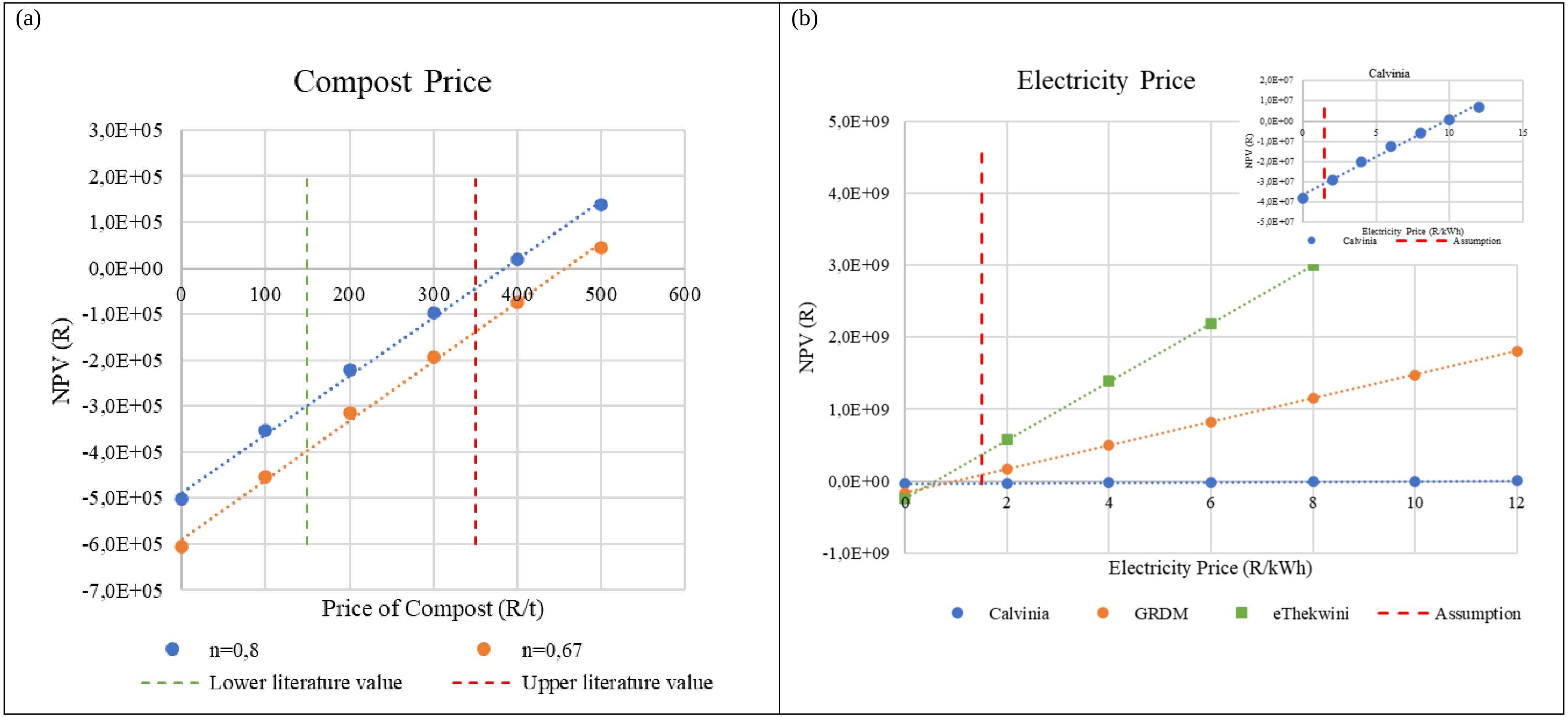


Figure 4-10: Sensitivity analysis for (a) the price of compost on the NPV for a scaling factor of 0.67 and 0.8 for Calvinia and (b) the price of electricity for all locations for AD (n=0.55089)

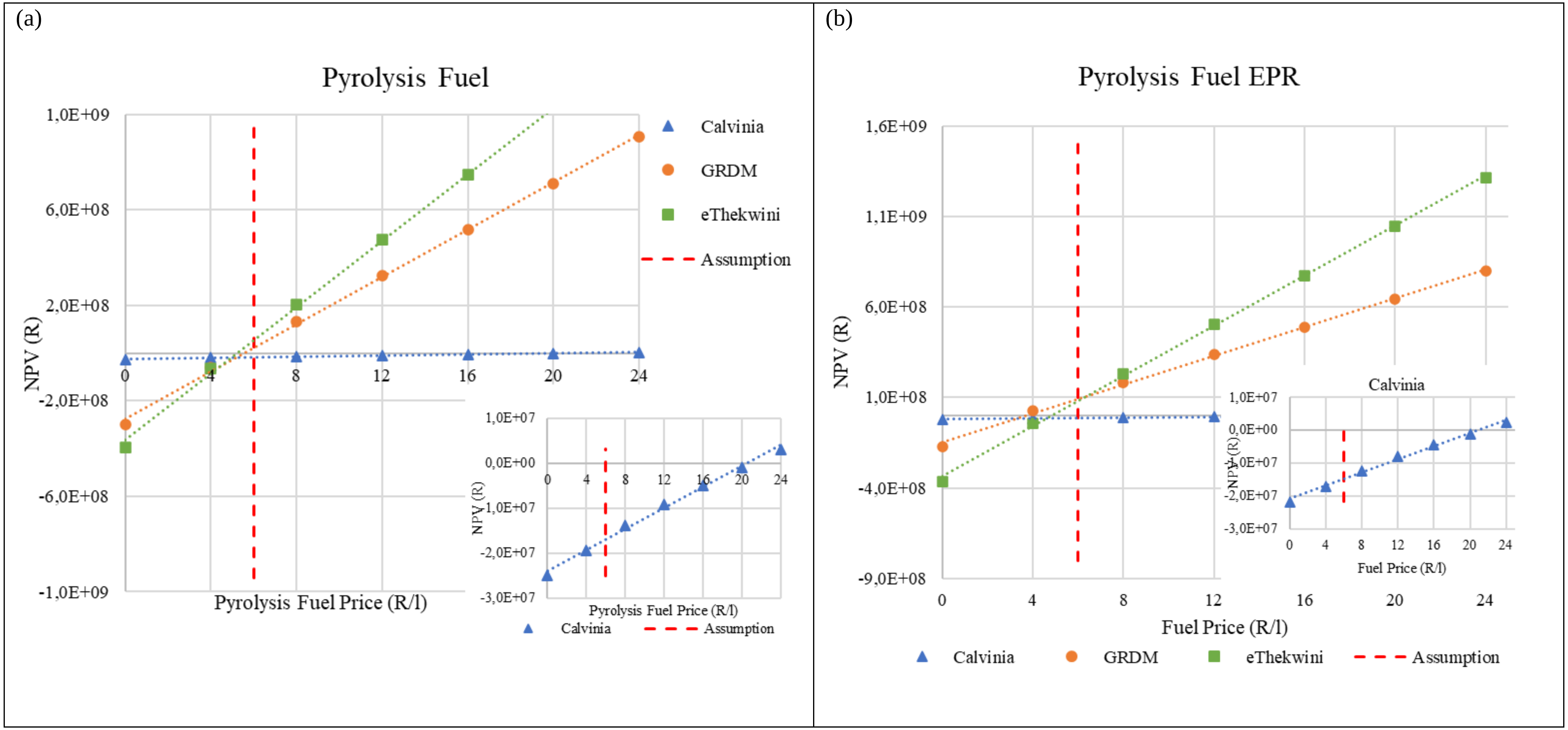


Figure 4-11: Sensitivity analysis of the effects of the price of pyrolysis fuel on the NPV (a) scenario 2(a) pyrolysis process and (b) Scenario 3 – pyrolysis with EPR targets

4.3.3. Recyclate price

The recyclate revenue includes glass, paper and cardboard, metal and recyclable plastics sales. Each stream was increased/decreased simultaneously while conducting the sensitivity analysis, noting that this might not be realistic as their prices may develop independently. Nevertheless, this analysis provides insights on the flexibility in recyclate sales given the introduction of EPR targets which are expected to influence the industry. Furthermore, the initial assumptions of the price of recyclables were higher (see section 3.1.1.) than the price provided for plastics by PETCO, which can be investigated through the sensitivity analysis.

The influence of recyclate price on the scenario was investigated while holding all other variables constant. The recyclate price for each product was considered between a ±40% change in costs for scenario one as presented in Figure 4-12(a). The recyclate price influences the income received. As expected, increased recyclate prices increase the unit credit per ton of waste in all locations. According to Figure 4-12 (a), Calvinia and GRDM are very sensitive to the recyclate price and cannot sustain a price decrease; however, eThekwini can retain feasibility at a recyclate cost of 90% of the assumed value for scenario 1. Scenario 2(a)-(c) required extremely high recyclate revenues to become feasible in Calvinia. The GRDM and eThekwini could sustain decreases recycling revenues by 40% and more for scenarios 2(a)-(c).

The percentage difference between assumed values and the EPR assumed values, CEPCI and PPI estimations are represented by vertical lines in Figures 4-12 and 4-13. The EPR and CEPCI prices closely correlated, with a percentage difference of 15 and 17% less than the assumed prices, while the PPI estimated a 17% higher cost. This means that if recyclate prices were according to the EPR (PETCO) estimations, processes would still be viable in most cases. Furthermore, scenarios 2(a)-(c) would be feasible at EPR, CEPCI and PPI estimations of the recyclate price for GRDM and eThekwini.

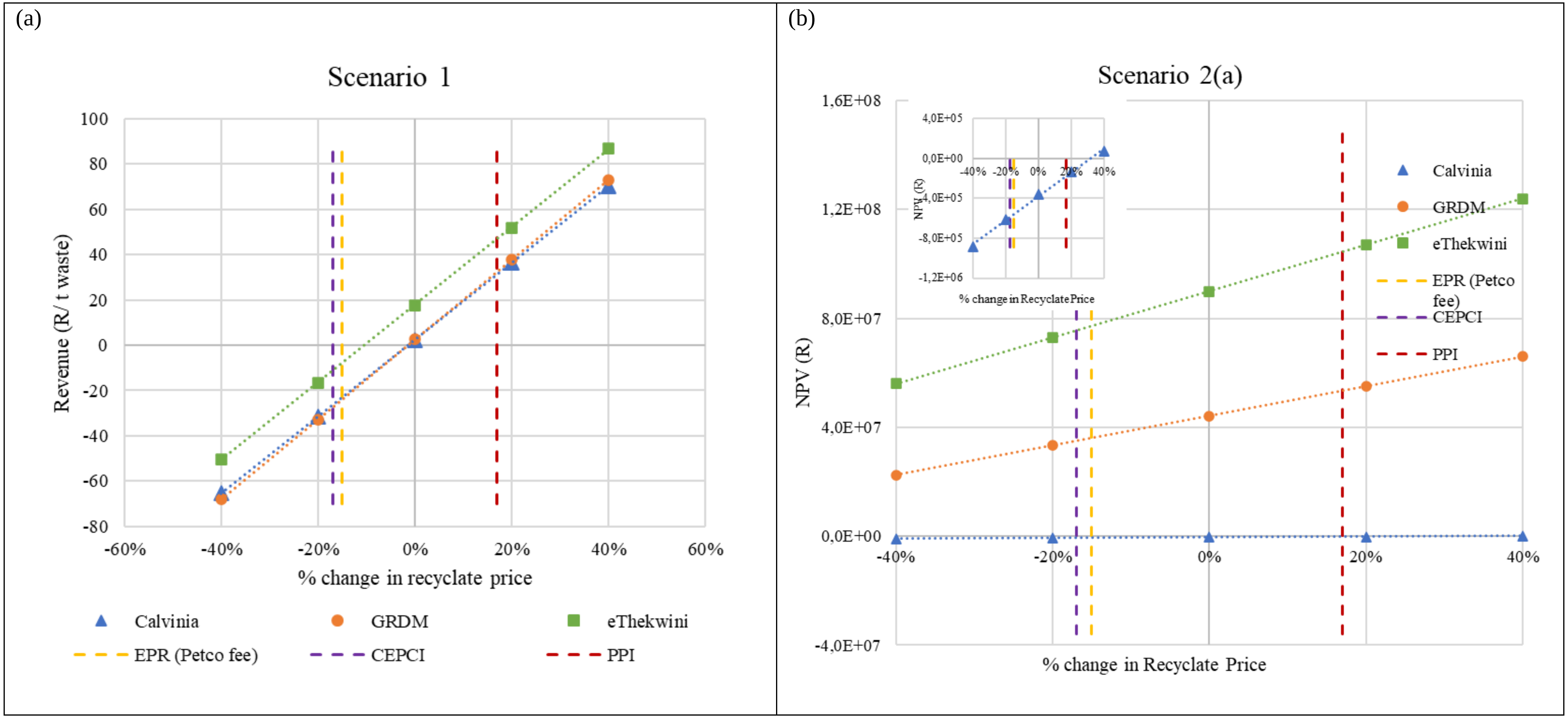


Figure 4-12: Sensitivity analysis of the effect of recyclate prices for (a) on revenue for Scenario 1 and (b) on NPV for Scenario 2(a)

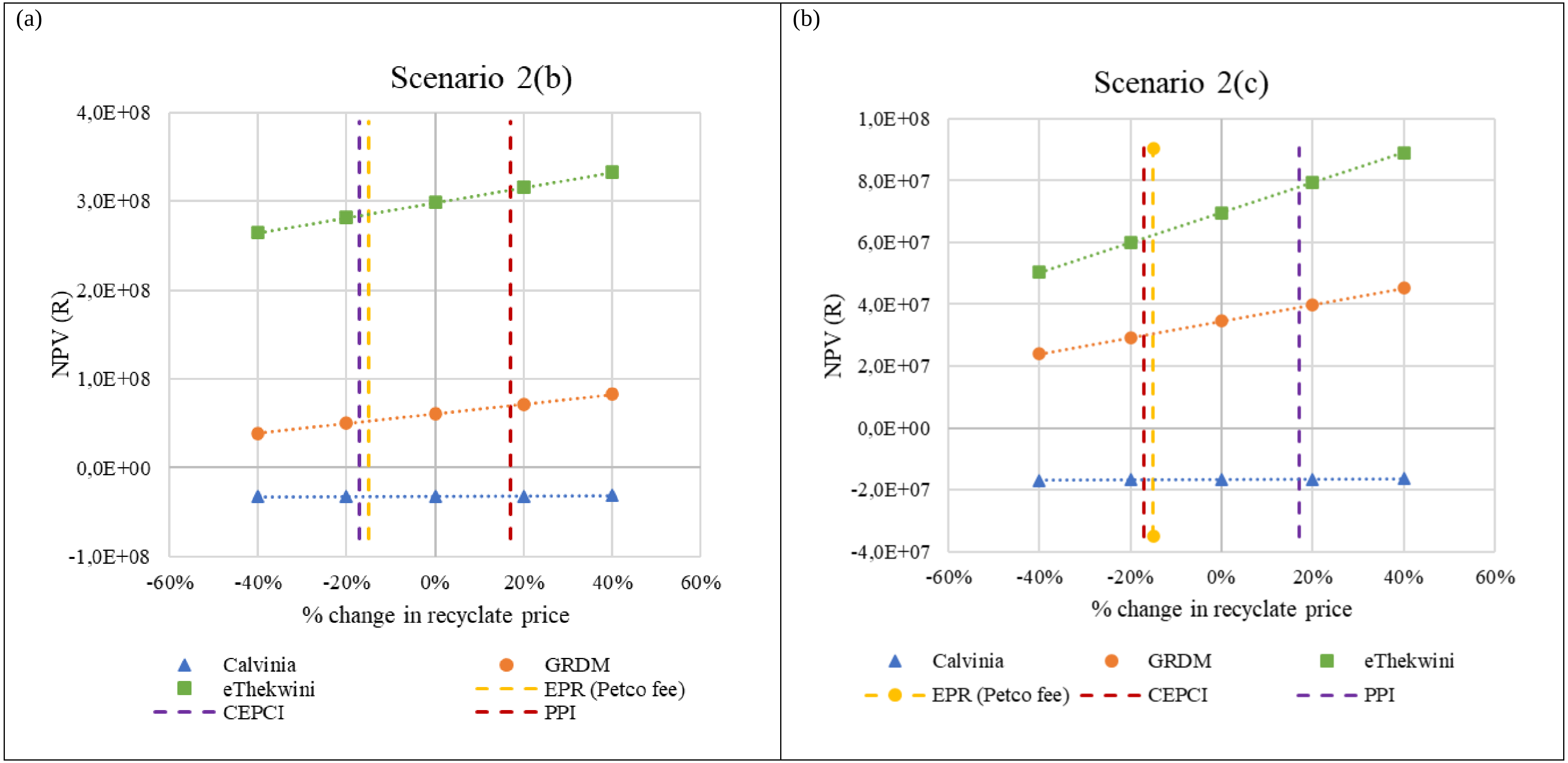


Figure 4-13: Sensitivity analysis on the recyclate revenue on the NPV for (a) scenario 2(b) and (b) scenario 2(c)

4.3.4. Landfill credit

The respective landfill gate fee was used as the 'landfill credit'. Therefore, an investigation of the landfill credit on overall feasibility is necessary. This credit can be considered a profit that the investor saves by diverting waste and could be used to buffer any reduced incomes from credits (landfilling, recyclate, product sale prices) and any increased expenditure (sorting costs, transport costs, OPEX).

The landfill credit was investigated through a sensitivity analysis for the range of R0 to 1000 /t waste, as mentioned in Table 3-15. The breakeven value for scenario 1 (at what landfilling credit will the total cost become zero) found the lowest possible landfill credit (base value: R584 R/t in Calvinia and GRDM; and 417 R/t in eThekwini) was R577.33 (1% decrease), R576.85 (1% decrease), and R365.55 (12% decrease) per ton of waste for Calvinia, GRDM and eThekwini (Figure 4-14 (a)). At a zero landfill credit, the overall costs for sorting and recyclate sales were approximately R200/t waste (Calvinia and GRDM) and R125/t (eThekwini), meaning that the scenario requires additional income to break even if no landfill credits are provided.

Similarly, all technologies (scenario 2(a) to (c)) exhibited an increase in NPV as the landfill credit increased. Composting and AD diverted the most waste through the processing of biogenic material, which made the bulk of the waste, resulting in lower landfill credits required to break even. Refer to Figure 4-14 (b) and Figure 4-15 (a) and (b). The composting process requires a minimum landfill credit of about R700/t for Calvinia, R400/t for GRDM and R190/t untreated waste for eThekwini. The processes of AD and pyrolysis behaved similarly when changes to the landfill credit were applied. Calvinia retained a negative NPV for the entire range (R0-1000/t). The landfill credit to break even was between R200-300/t for both processes in the GRDM. While eThekwini produced feasible results throughout the range and could sustain zero-landfill credits for AD and pyrolysis.

Nahman (2021) found that the standard waste disposal fee and waste tariffs (from generators for waste collection), and landfill tipping fees are much lower than "what should be paid" in the country. This might lead to the over assumption of credits when considering diverted waste streams since the actual gate fees might be less than assumptions. The drawback of such a scenario means that the profit or "buffer credit" as mentioned above becomes lower.

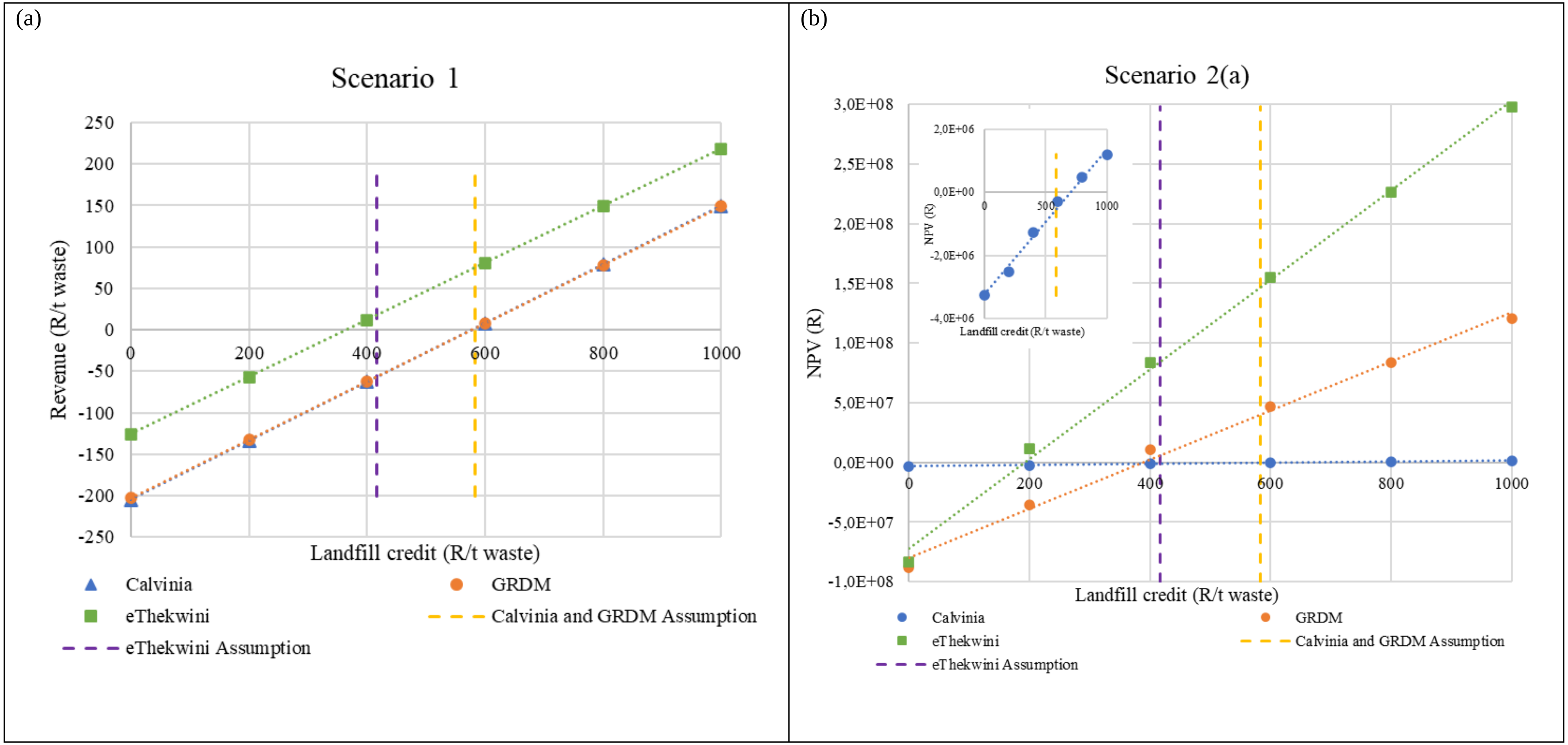


Figure 4-14: Sensitivity analysis of the effects of landfill credit for (a) Scenario 1 and (b) Scenario 2(a)

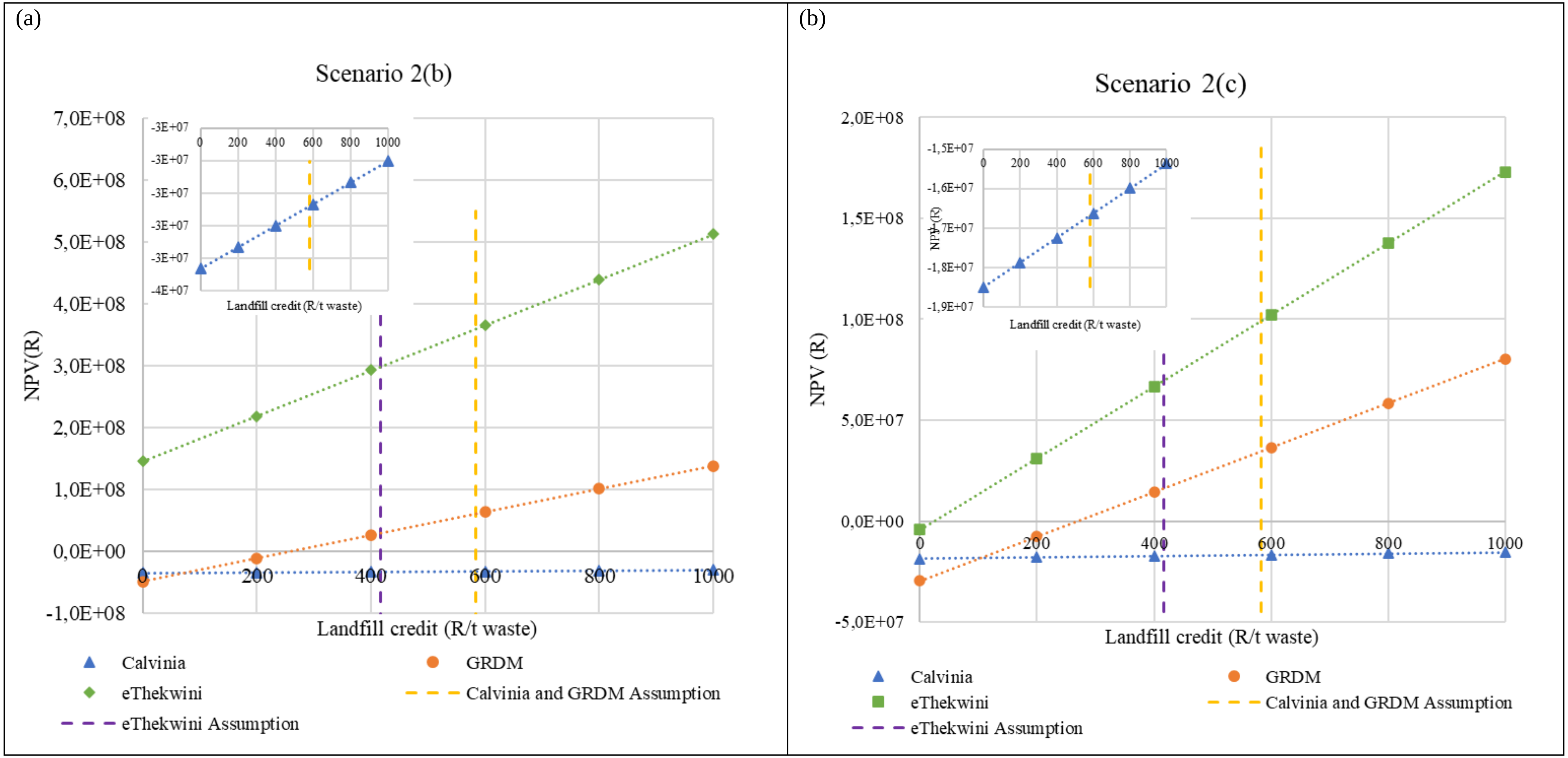


Figure 4-15: Sensitivity analysis of landfill credit for (a) Scenario 2(b) and (b) Scenario 2(c)

4.3.5. Zero landfill credit

As mentioned in section 4.3.4., the exact landfill credit is unknown and might be zero or much lower than the assumptions in some cases, such as rural municipalities. For example, Nell and Schenck (2018)found no access control in Calvinia, resulting in no revenue generation at the landfill site. For this reason, the breakeven point for the different variables was considered at a landfill credit of zero. Scenario 2(a) was selected to show how zero landfill credit would affect the various parameters.

Transport cost

These results for the effects of zero landfill credit on the transport costs are presented in Table 4-10. The transport distance is needed to decrease to about 48km, 22km and 19km or a transport cost of R0.18/t/km, R0.65/t/km or R0.84/t/km for Calvinia, GRDM or eThekwini to breakeven (at landfill credit of zero). Conversely, the sorting process will need to produce a credit (representative by the negative value), which was not possible. Finally, a higher recyclate price for each stream would be able to promote feasibility at each location.

Table 4-10:Analysis of the different parameter breakeven points for a landfill credit=0

	Calvinia	GRDM	eThekwini
Transport distance (km)	47.97	21.8	18.76
Transport cost (R/km/t)	0.1766	0.654	0.844
Transport cost (R/t)	78.67	98.15	84.44
Sorting cost (R/t)	-62.25	-60.85	-15.82
% increase in recycle fee (%)	175	102	74

The effects of different parameters on the NPV were investigated for a landfill credit of zero at n=0.67. Similar trends are expected for =0.8 for composting. Similar trends were expected to be true for AD and pyrolysis.

Compost Price

The compost price was investigated at a landfill cost of zero. The general trend found that an increase in landfill credit increased the NPV. eThekwini requires the lowest composting price to break even (approximately R450/t), while GRDM requires a higher price of R1 400/t. Calvinia requires the highest compost sales to counter the zero landfill fee of approximately R2 300/ t compost. eThekwini produces the highest amount of compost, which could explain the lower price while the lower volumes in GRDM and Calvinia require the highest compost prices. Refer to Table 4-11.

Table 4-11: Analysis of breakeven points for composting at landfill credit=0

	Calvinia	GRDM	eThekwini
Minimum compost price (R/t)	2300	1400	450
Difference (%)	1 433	833	200

4.3.6. Recyclate credits

According to the cost allocation, at a zero landfill credit, the separation and recycling operation requires money rather than providing a credit, decreasing the overall sales income of the project. The percentage difference between the recyclate revenue at breakeven (landfill =0) was 304%, 105% and 243% for Calvinia, GRDM and eThekwini, presented in Table 4-12.

Table 4-12: Sensitivity analysis of recyclate revenue on composting at zero landfill cost

	Calvinia	GRDM	eThekwini
Recycle Revenue (Landfill =0)	-229 507,75	-12 504 107,86	-7 234 885,37
Recycle revenue to break even	468 260	564 393	10 378 197
Percentage Diff	-304%	-105%	-243%

Therefore, from the results presented by scenario 1, it is evident that higher recyclate revenues and product sales or lower transporting fees will be required for the different processes to break even at a zero landfill credit. However, some cases, like eThekwini scenario's 2(b), 2(c), and 3 could sustain zero landfill credit.

4.4. Impact Assessment

The results from the impact assessment are represented in Figure 4-16. The impact assessment is divided into six categories, each with sub impacts. Specific categories are scenario-inherent and hence similar for the individual municipalities, discussed first. The technical category comprises conversion, amount of waste diverted and TRL, as well as the environmental impact category assessing (on a qualitative basis) the potential for emissions/pollution.

In the second part, other categories which are scale dependent and hence differ between the locations are discussed. These include the economic, TEA, social and legislation categories. The economic sub-categories are CAPEX and OPEX. The TEA sub-categories investigated the NPV, PBP and IRR. The social category assesses the job opportunities created. And lastly, the legislation was rated based on the most (high) and least (low) legislative requirements.

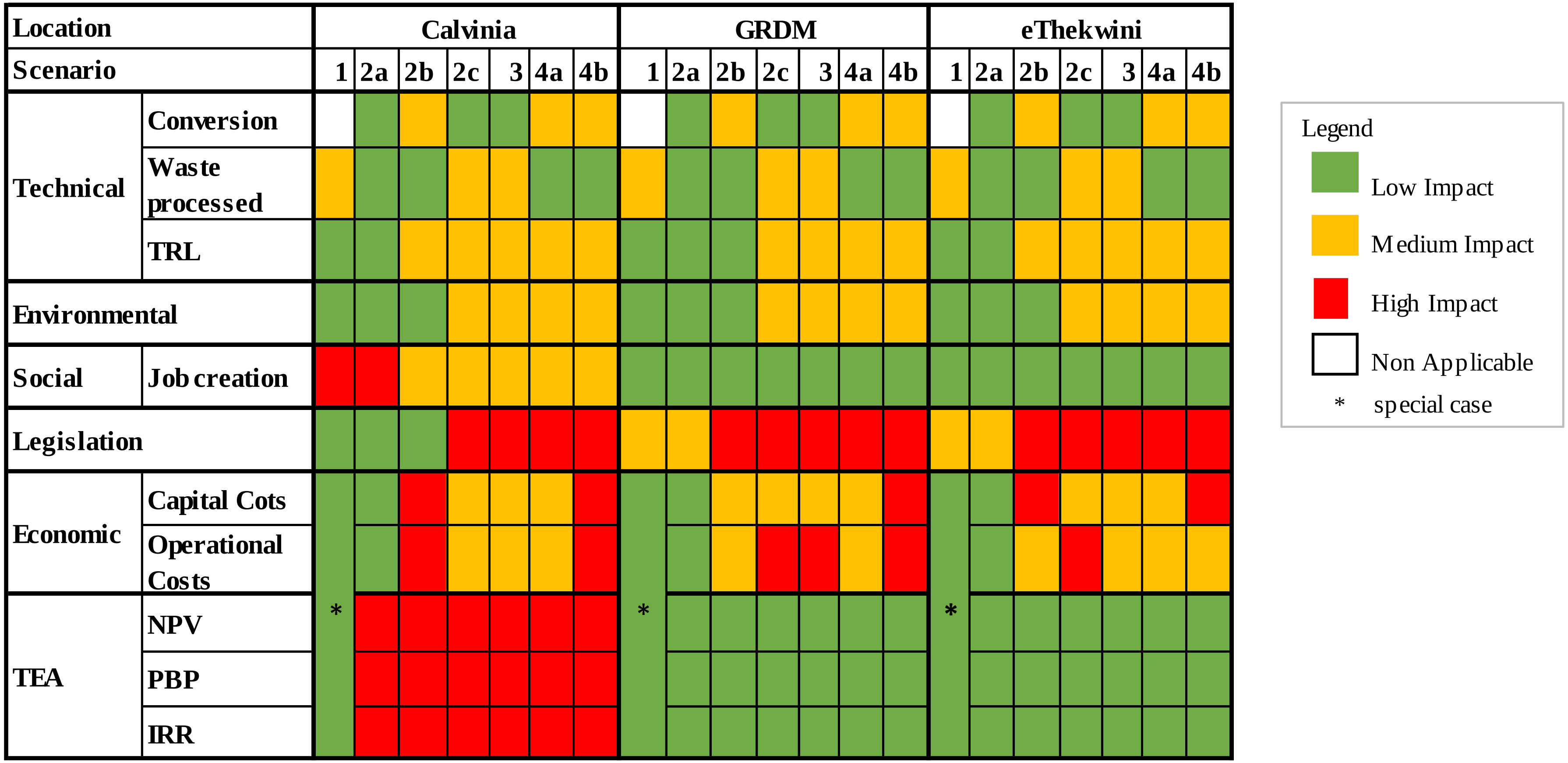


Figure 4-16: Impact assessment for each scenario based on location

***A positive effect is green, associated with favourable conditions, and negative effects are defined in red with the least favourable attributes. Orange colour represents a medium effect, which lies between the two extremes in the impact assessment*

Scenario 1 focused on sorting waste and diversion of sorted fractions to recycling initiatives, resulting in the least amount of waste (around 44%) diverted since all other scenarios also included recycling (medium effect). The TRLs of sorting facilities are relatively high, with many functioning Material Recovery Treatment stations, such as in eThekwini. The sorting and separation of waste should not pose an environmental hazard since there is no thermal or chemical waste treatment. Nevertheless, labourers should wear the appropriate protective equipment when handling waste. Water pollution may be possible through washing waste, but this should not occur under the correct design of the facility.

Scenario 2(a), i.e. composting, features a high conversion of waste into compost with a yield of 75%. With a waste diversion of between 60 (GRDM) and 72 % (eThekwini), this category is ranked with positive effects. Composting is a mature technology (high TRL) used for generations and has been studied extensively, with multiple composting facilities in South Africa. When designed appropriately, composting has low pollution and carbon emissions than thermal technologies. Therefore, these aspects are considered as positive impacts. Furthermore, the composting process should not cause impacts on human health (Couth & Trois, 2012). Composting has a high public acceptance (low risk) and low health impacts (low impact).

On average, scenario 2(b), i.e. AD features about 55% conversion, is considered a medium impact. The waste reduction potential ranges between 62 and 72%, considered a positive effect. In South Africa, since there has been a low uptake and general inexperience in designing, constructing and operating biogas facilities; biogas is regarded as a nascent or infant industry (Gogela, et al., 2017). Although AD is a mature technology globally, in South Africa, the TRL will be associated with a medium effect. Similar to composting, appropriately designed facilities have low pollution and carbon emission potentials compared to thermal technologies with a general high public acceptance and low health impacts. Overall, this results in a positive environmental impact when compared to landfilling.

With regards to waste diversion, Scenario 2(c) and 3 (pyrolysis) divert a moderate amount of waste (around 35%). Particularly fast pyrolysis is still at the demonstration or very early commercial phases (TRL 6 and TRL 7). In South Africa, there are not many proven pyrolysis facilities so a medium effect will be considered. The pyrolysis process had a high conversion of over 80%, which was attributed to a positive effect. The process produces lower emissions than waste incineration processes (SOx, NOx, heavy metals, dioxins, furans). Therefore a. moderate environmental footprint was considered (orange).

Scenario 4(a) and (b) comprise the combined effects of their treatment processes. The low conversion of the pyrolysis scenario is ameliorated by either composting or AD. Due to the fact that both the biogenic and plastics fractions are treated, the "waste processed" is high, with between 60 and 72% of the waste diverted from landfills.

The legislation aspect is scale dependent. Some of the basic regulations and licencing are described below (please note that this is a brief summary, and details may have to be separately addressed):

Scenario 1 (sorting and recycling) is subject to standard legislation as per categories discussed in NEM: WA, resulting in the main licencing requirement. Furthermore, the scenario will have to adhere to all municipal by-laws and corresponding legislation related to NEMA, NWMS and Air and Water Acts.

For the scenarios involving waste stream processing, the legislative requirements for composting (scenario 2a) could be considered the lowest since no AQA or gas handling licenses are required. However, basic assessments are required for facilities with waste treatment between 10 and 100 tpd, meaning these are needed in the GRDM and eThekwini (DEA, 2013). However, as discussed in section 2.3.5., the composting norms and standards aim to exempt composting facilities from requiring licencing in the future, which will lessen the cost and time associated with a waste licence. Furthermore, the proposed changes to the composting norms and standards for exempting processes more than 10 tpd means that costs and legislative requirements might promote the uptake. In addition, the Best Practicable Environmental Practice of composting of organic waste will need to be adhered to according to the National Organic Norms and standards. The scenario will also be subject to all regulations in NEMA, NWMS and Water Act. This led to a ranking in green for all municipalities.

AD (scenario 2b), in addition to the above waste regulations, requires additional gas handling licenses and electricity generation licencing. Basic assessments are required for facilities with waste treatment between 10 and 100 tpd, meaning these would be needed in the Garden Route and eThekwini (DEA, 2013). Possible licencing as per the Department of Energy include regulations by NERSA and the electricity act. The scenario is also subject to NEM: AQA and the Water Act. Hence, AD was ranked green for Calvinia, but due to the larger legislative uncertainties in the GRDM and eThekwini, these were ranked red.

According to legislation, pyrolysis and gasification are considered incineration processes (although scientifically, incineration is defined as combustion in the presence of oxygen), needing licenses and tests for different materials (waste license, EIA, and Air emissions license, for production greater than 2/3 L per day). Similar to incineration, the legislative requirements are associated with a high impact risk for pyrolysis. Furthermore, if considered WTE, the same legislation as AD is required. These legislative policies apply to scenarios 2(c), 3, and 4(a) and 4(b).

Long-term contracts with a municipality are governed by Section 33 of the Municipal Finance Management Act, which are typically shorter than the usual payback period of waste technologies (MFMA, Act 56 of 2003). WtE projects might further trigger laws around water usage, land use and air quality, extending the project development phase by five years (GreenCape, 2016). Therefore, it is crucial to appoint a suitable environmental assessment practitioner (EAP) with previous experience in the waste sector and detailed knowledge of recent legislation changes. The lack of coordination between government departments on thresholds and timeframes can result in additional unplanned costs (GreenCape, 2016).

In the following sections, the economic, TEA and job creation categories are discussed:

Scenario 1 is based on the sorting and recycling of waste and does not follow the scaling calculations performed for the other scenarios (special case represented by * in Figure 4-16). Instead, the calculation is based on a published sorting cost, irrespective of scale. Therefore, the economic impact assessment is based on one single indicator, the revenue received from the process. The revenue received was positive for all locations with values of R2.3/t, R2.5/t and R17.5/t. All locations made a profit and thus has a positive effect (green). The number of jobs are low at two for Calvina (red) but increased t over 100 for GRDM and eThekwini, represented by green.

For Calvinia, the capital cost was lowest for Scenario 2(a) (R119 248), medium for scenario 2(c), 3 and 4(a) (~R9-10 million) and highest for scenario 2(b) (R16.4 million) and 4(b) (R27.4 million). The operational cost followed the same trend and was lowest for Scenario 2(a) (R166 417), medium for scenario 2(c), 3 and 4(a) (~R2.6- 4.5 million) and highest for scenario 2(b) (R4.8 million) and 4(b) (R7.3 million). The techno-economic parameters of interest (NPV, IRR, PBP) were unfavourable for all scenarios, indicating a high impact. The total number of jobs were 2,4,12,12,14, and 22 for scenarios 2(a), (b), (c), 3, 4(a) and (b), respectively.

For the GRDM, the capital cost was lowest for scenario 2(a) (R1.6 million), moderate for scenario 2(b), 2(c), 3 and 4(a) (~R145 million) and high for scenario 4(b) (R289.7 million). The operational cost was lowest for Scenario 2(a) (-R7.6 million), moderate for scenario 2(b) (R18.8 million), 4(a) (R20.8 million) and highest for scenario 2(c), 3 (R30.4 million), and 4(b) (R46.9 million). The techno economic parameters of interest (NPV, IRR, PBP) were favourable (low effect) for all scenarios, except scenario (high effect). The total number of jobs was lowest for scenario 2(a)-(b) (111-115) and increased to 160 in scenario 4(b). All scenarios have a positive effect regarding job creation (green).

For eThekwini, the capital cost was lowest for scenario 2(a) (R3.0 million), moderate for scenario 3, 2(c) and 4(a) (R173.7 -R192.6 million) and highest for scenario 2(b) and 4(b) (R241.9 and 431.6 million, respectively). The operational cost was lowest for Scenario 2(a) (-R11.7 Mio), highest for scenario 2(c) (R70.2 million), and medium for 4(b), 2(b), 2(c) and 3 (R27.5-R43.2 million). The techno economic parameters of interest (NPV, IRR, PBP) were favourable (low effect) for all scenarios, except scenario 3 (high effect). The total number of jobs was high for all scenarios, with a minimum of 160 jobs (scenario 1) and a maximum of 226 jobs (scenario 2(c) created.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

The outcome of the study addresses the aim to determine which waste treatment options are economically viable in the considered municipalities. The results can also be transferred with minor adjustments to other municipalities and technologies. The study further achieved the objective of investigating local waste profiles to determine economic variability in decentralised locations by using Calvinia as a case study. The study further assessed the effects of size and scale through the investigation of the GRDM and eThekwini municipalities. Overall, the techno-economic assessment provided insights into the feasibility of various waste treatment processes, namely composting, AD and pyrolysis in three municipalities of South Africa by comparing the Net Present Value, Internal Rate of Return and Payback Period. For this assessment, it is assumed that the technologies investigated are already process fit and design and model considerations have already been considered. Thus, the key parameters investigated relate to the capital and operational costs. Several economically feasible scenarios have been identified. Municipalities wanting to implement such strategies in their waste management are encouraged to collect quotations for the plants suitable for their waste volume and validate the accuracy of the data used in this order-of-magnitude study to improve the certainty of the economic forecast.

Based on the results of the study, the recommendations regarding the choice of viable waste treatment options are as follows: Scenario 1 was economically viable in Calvinia, indicating that decentralised separation and recycling of waste is possible and should be considered in remote locations. However, scenarios with higher capital and operational costs (2(a)-(c) and 3) were not feasible, and none of the parameters investigated in the sensitivity analysis could provide for a viable business case (within reasonable limits). In such cases, incentives and government funding schemes would need to be investigated to support waste treatment opportunities in decentralised locations. As scale increased, all investigated scenarios were feasible in GRDM and eThekwini, except for scenario 3 (pyrolysis with EPR targets), indicating that the possible combination of waste from different decentralised locations (i.e. multiple smaller municipalities like in the GRDM) could result in possible feasible treatment options in these parts of the country. It should be noted that smaller, decentralised municipalities suffer from the economy of scale and as scale increases, the amount of revenue positively overcomes costs. Furthermore, the much further distances for transport required by decentralised municipalities affects the operation’s feasibility. Hence, if recyclers were installed closer, recycling would be promoted.

It is hoped that this research will be of value for works of national importance, such as the Waste-to-Energy roadmap and items of decision making. Furthermore, the assessment successfully considered the evolving legislative environment, by looking at the effect of the EPR regulations on pyrolysis. This study can be extended in the future. A holistic analysis of waste treatment scenarios was provided in the impact assessment in Figure 4-16, further highlighting the importance of such assessment and consideration of multiple criterias in waste management. Finally, another two important conclusions can be drawn from this study. Firstly, municipalities should consider the value of the waste they have access to and understand that outsourcing the collection of recyclates from households reduces their opportunity to derive revenue. This study clearly shows that recyclate revenue is important to sustain the financial viability of waste treatment plants appended to the sorting facility. Secondly, this study has also demonstrated that while the EPR is commendable, it affects businesses wanting to build waste treatment plants, as it introduces uncertainty about the availability of the targeted waste fraction in the future over the plant's lifetime. However, plastics-converting pyrolysis should be considered for urban mining operations at landfills.

Treatment specific conclusions were as follows:

The separation and recycling of waste resulted in a credit of R2.3 /t waste, R2.5/t waste, and R17.7 t/waste annually. The credit per ton of waste processed in each facility indicates that at the assumptions, scenario 1 was feasible in Calvinia, GRDM, and eThekwini. The general trend showed that as sorting costs increased, the overall revenue decreased, and the plant began not to be feasible at a certain sorting price. A breakeven sorting separation cost of R144.31/t, R144.15/t, and 159.54 R/t could be afforded for Calvinia, GRDM, and eThekwini. The assumption of the same cost for sorting (R/t) for all municipalities means that scaling cannot affect the economics. However, a lower transport cost may allow for higher sorting costs while still breaking even. The transport cost could be increased in Calvinia to R1.65/t/km (400 km) or 404.1 km (at R1.64/t/km), at which the project will break even. In GRDM, the unit transport cost needs to decrease to R3.36/t/km (at 150km) or a distance of 121.7 km (at R4.50/t/km) to break even. eThekwini has a similar trend to Calvinia, where the unit cost could be increased to R5.01/t/km (at 100km) or a distance of 111.5 km (at R4.50/t/km) to reach the breakeven point.

The financial indicators for the AD system exhibit poor economic feasibility in Calvinia with the NPV less than zero irrespective of the scaling factor (0 to 1.2), implying that the OPEX is too high to provide feasible results. Based on cost allocation, as the amount of feed increases (with capacity increases), in Clavinia, due to the much smaller amounts of organics, the size of AD units is still very small compared to GRDM and eThekwini. In this case, Calvinia can overcome the costs associated with larger processes as feed increases. The breakeven cost of electricity was R9.8/kWh (base - 1.3 R/kWh) in Calvinia. With lower electricity prices to break even of R0.9/kWh and R0.6/kWh, respectively, in GRDM and eThekwini.

The production costs for the pyrolysis process were determined at R5 256, R1 000, and R898/ t waste diverted. This resulted in a negative NPV in Calvinia (-R16.7 million) but positive NPVs in GRDM and eThekwini. A decrease in NPV with the implication of EPR regulations (R17.6 to -R15.9) at all locations, with the worst performance in Calvinia, indicates that the project is not feasible to investors at current assumptions. However, IRRs of 10.4% and 17.73% for GRDM and eThekwini, suggest that the project becomes feasible in these locations at that lower discount rate. The liquid product of pyrolysis, a heavy fuel substitute, can be used to supply local communities with fuel at a much lower price. The minimum fuel price for scenario 2(c)- pyrolysis would require R20.9/l in Calvinia, while the price decreases from the base value of R6/l to R5.3/l for GRDM and R5.0/l in eThekwini. Lower fuel prices are possible in GRDM due to the higher pyrolysis feed fractions (higher plastic compositions) than Calvinia and eThekwini. Much higher prices of R26/l (333% increase), R7.3/l (22% increase), and R6.3/l (5% increase) for Calvinia, GRDM, and eThekwini, respectively (from the base case of R6/l) are expected for the EPR regulated scenario 3.

Combined scenarios found that, similar to the stand-alone processes (composting or pyrolysis), the combined process (scenario 4(a)) was not feasible in Calvinia. The combined scenario (scenario 4(a)) is less attractive than composting (scenario 2(a)), with lower NPVs and higher PBPs in GRDM and eThekwini. The combined scenario (scenario 4(a)) is more feasible than the standalone pyrolysis process (scenario 2(c)) with greater NPVs and lower PBPs (by one year) in GRDM and eThekwini (base of 5 years). In GRDM, pyrolysis with composting combined is more favourable, while in eThekwini, pyrolysis and AD are more economically favourable. Revenue from biogas production could be higher than compost sales in eThekwini, which has a higher biogenic waste fraction.

5.2. Limitations and Knowledge Gaps

- Most recent waste characterisations were noted for 2018, 2019, and 2010 for Calvinia, GRDM, and eThekwini. It is noted that eThekwini data is over ten years old, and significant changes to the waste profile may have occurred. However, since no more recent waste study was conducted, the 2010 data served as the most comprehensive study.
- The CAPEX of technologies was based on historical plants for composting. However, no industrial plant data was available for anaerobic digestion and pyrolysis. As such, these costs

were based on previous investigations for AD and a pilot plant study for pyrolysis. These are deemed suitable for preliminary assessments.

- The exact transportation costs are difficult to estimate, thus, these costs are based on an assumed transporting distance and costs of a typical truck haul transporting goods for a one-way trip. These costs were based on previous fuel prices, which have drastically increased over the past year. A sensitivity analysis performed on the recyclate prices indicates market fluctuations in the different variables affecting costs (such as fuel or distance).
- A simple OPEX was conducted as mentioned in chapter 3.6, and intensive mass or energy balances were not included in the costs. Instead, process waste disposal and energy costs were considered a percentage of the Total Production Costs.
- Recyclate costs were based on 2011/2012 data since it was the most comprehensive data available. These values were escalated using CECPI and PPI values for the years in question. A later comparison was made between recyclate prices published by PETCO and shows minor differences from the assumed prices.
- Full technical feasibility requires one to consider more factors than what was possible in this study. However, it is assumed that technologies have already been designed considering such factors (i.e. operation and safety). This study does hence not consider all these factors.

5.3. Recommendations for municipalities and policymakers

- During this study, due to COVID-19 restrictions, sampling of the waste was not possible. Therefore, waste characterisation data was based on previous assessments of the respective municipalities. It is therefore recommended that municipalities with updated waste characterisation studies publish such work regularly to aid researchers in capturing the latest data. Alternatively, waste characterisation studies should be undertaken in municipalities who are intending to use alternative waste treatment options is necessary.
- Furthermore, South Africa largely disposes of waste in landfill due to the much lower (apparent) costs involved. Technology data was not readily available and was highly dependent on previous studies. Therefore, it is recommended that policymakers, where possible, promote the knowledge-sharing platform for alternative waste treatment by encouraging industry and academic research. However, it should be noted that this assessment uses these technologies as examples; therefore, where more recent data is available, it is encouraged to substitute these parameters in the present model to increase the accuracy of such a feasibility study.
- Expertise in waste management, in general, is lacking within the country, and policymakers must consider such studies to inform and assist municipalities. Where possible, the presented

methodology with updated waste characteristics and technology costs should be used to determine baselines for other municipalities in the country.

- Municipalities are encouraged to implement simple treatment options such as separation and recycling for smaller decentralised municipalities such as Calvinia but consider more robust and higher capital-intensive technologies for higher scaled options since they are economically feasible.
- The landfill credit can be considered a key parameter since the true cost of landfilling is not widely recognised and may be underestimated. This is exhibited by the minimum landfill cost of R577, R711, and R365/ t waste for the feasibility of the separation and recycling scenario.
- As shown by the investigation of scenario 3- EPR regulations, municipalities and policymakers are encouraged to consider legislative instruments when looking at feasibility to accurately account for imposed changes in the waste landscape.

5.4.Recommendations for future work

The following recommendations should be considered to expand on and enhance results from this study:

- Perform waste characterization studies on a specific location to provide more accurate and localised solutions for regions under investigation.
- Conduct experimental studies on the performance of specific treatment options using waste fractions from specific locations to validate yields. This would allow for more accurate product costs to be established.
- Conduct a feasibility study for urban mining of plastics directly from landfills to supply feedstock for pyrolysis.
- Using up-to-date quotes, investigate universal assumptions for CAPEX and OPEX calculations for each waste process based on the process and equipment specifications.
- Use the methodology in this study to investigate other treatment options which were not considered (such as gasification and incineration).
- Due to the fluctuations in fuel prices in South Africa, further study investigating the effects of the fuel price on the feasibility of waste services in the country is encouraged.

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APPENDIX A: DEFINITIONS

This section provides definitions of terms used throughout the dissertation.

Compost

According to the Regulations, compost is defined as a fully decomposed substance(which is both stabilised and homogenous) of animal or plant origin free of plant nutrients additives and harmful substances or elements (DEA, 2012(b); DEA,2013).

Composting

Composting is the process that converts organic materials to compost, as described above, through bacterial and fungal decomposition. The compost quality depends on the materials used in the composting process (National Research Council, 2000).

Domestic Waste

Domestic waste consists of various wastes mainly for residential, educational, health care, sport, or recreation purposes and does not consider hazardous waste (DEFF, 2020a).

Enumerated Area (EA)

Medani 2016, of Market Decision, formulated a globally aligned set of settlement type classifications based on information taken directly from Statistics SA by Enumerated Area (EA) type. This classification is not final because the government and the private sector will need input (Medani, 2016).

Table A-1: Market Decision classifications of localities by population size and the average population of some EA types (Medani, 2016)

Enumerated Area (EA) type	Population Size Range	Average Population Size
Metro	500 000 and more	2 263 529
Large city	350 000 to 499 999	495 383
Medium city	200 000 to 349 999	258 947
Small city	100 000 to 199 999	143 637
Large town	50 000 to 99 999	74 899
Medium town	20 000 to 49 999	37 392
Small town	10 000 to 19 999	13 070
Large village	5000 to 9999	No data
Small village	1000 to 4999	No data
Settlement	up to 999	No data
Rural	rural and farms	No data
Informal settlement	Varies	No data

Household

According to Statistics SA, a household is characterised as a group of persons who live together and provide themselves jointly or individually. Note: The persons occupy a common dwelling unit (or part of it). Furthermore, if the same dwelling is shared but food or other essentials are not shared, they are separate households (Stats SA).

Urban areas are typically defined as densely settled and developed

Metropolitan formal, these are inclusive of large townships joined to metropolitan areas.

Rural areas are characterised by scattered population distribution. These are usually tribal areas or previous homeland areas (Atkinson, 2014).

Municipal Solid Waste (MSW)

MSW consist of non-hazardous waste produced by households, commercial premises, public or private institutions, and other sources. This waste group includes food waste, yard waste, durable and non-durable packaging, metals, glass, etc. (Sajjad, et al., 2019).

Incineration

The process of burning solid waste under controlled conditions reduces its weight and volume and often produces energy.

Organic Waste

The National Organic Waste Composting Strategy (2013) defines organic waste as a carbon-based animal or plant origin material. Organic waste may also be categorised as the combination of garden waste, food waste and wood waste (DEA, 2011).

Recycle

Recycling is a waste recovery process that reclaims waste to further separate waste for further use and the processing of that separated material as a product or raw material (DEA, 2008).

Reuse

The reuse of waste intends the utilise articles from the waste stream again for a similar or different purpose without changing the form or properties of the articles (DEA, 2008).

Recovery

The term ‘recovered’ means to recover materials from waste. These resources are then available to divert waste reuse, recycling or recovery (including energy recovery) activities. Recovery should be considered after reuse and recycling initiatives.

Treatment

Any method, technique or process that is designed to (a) change the physical, biological or chemical character or composition of waste; or (b) remove, separate, concentrate or recover a hazardous or toxic component of waste; or(c) destroy or reduce the toxicity of waste, to minimise the impact of the waste on the environment before further use or disposal (DEA, 2008).

Solid Waste Management

The handling, treatment or disposal of waste or any related activities is considered solid waste management, including the supervised handling of waste from origin to the final disposal.

Waste

Municipal waste in SoWR is defined according to NEM: WA as the waste stream(not hazardous waste) originating from premises used for residential, educational, health care, sport or reaction purposes (DEA, 2018). This waste stream excluded mainline recyclables (paper, plastics, glass, metals and tyres), organic waste (food and garden waste), commercial and industrial waste and construction and demolition waste (DEA, 2018).

Waste Management Hierarchy

According to Oelfse (2013), the waste management hierarchy promotes alternatives from landfilling. As outlined by the NEM: WA (2008), landfilling is the least preferred waste disposal option and should only be considered after other waste management options have been exhausted, including minimisation, reuse, reduction, recycle or treatment to reduce waste going to landfills (Oelofse, 2013).

Waste to Energy (WTE)

Waste to Energy (WtE) is the process of converting waste into electricity, syngas, biogas, or heat as the use of a thermal method (combustion, thermal gasification, pyrolysis and plasma arc gasification to generate heat for electricity) (Adenuga, et al., 2020).

APPENDIX B: ADDITIONAL/SUPPORTING DATA

Techno-economic assessment

Table B-1: CEPCI Indices used for calculation purposes for 1996 to 2016 (Turton, et al., 2018) and 2017-2020 (Chemengonline, 2019)

Year	Index
1996	382
1997	387
1998	390
1999	391
2000	394
2001	394
2002	396.6
2003	402
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	612.7
2019	607.5
2020	596.2

Table B-2: Location Index according to WEF global competitiveness report for 2019(WEF, 2019). The index for 2020 was not published due to the global pandemic (WEF, 2020). Thus, 2019 indices were used for relevant calculations.

Country	Index 2019
South Africa	62
United Kingdom	81.2
United States	83.7

Table B-3: Currency conversion factors (X-Rates, 2021)

Year	ZAR/USD	ZAR/GBP	ZAR /EURO
2020	15.77	21.09	17.76

APPENDIX C: MASS BALANCES AND SAMPLE CALCULATIONS

C.1. Mass Balances

Table C-1: Mass balance for (a) Sorting and recycling of recyclate (tpa)

	Calvinia				GRDM				eThekwini			
Waste Fraction	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**
Biogenic	528	0	0	**528**	26 470	0	0	**26 470**	65 905		0	**65 905**
Glass	40	160	0	**200**	1 435	5 741	0	**7 176**	2 283	9 133	0	**11 416**
Metal	13	51	0	**64**	590	2 359	0	**2 949**	1 359	5 438	0	**6 797**
Paper and Cardboard (Mixed)	42	169	0	**212**	2 649	10 596	0	**13 245**	4 524	18 098	0	**22 622**
Rec Plastic (Mixed)	46	185	0	**231**	2 929	11 715	0	**14 643**	3 859	15 436	0	**19 295**
Non Rec Plastic	73	0	0	**73**	0	0	0	**0**	1 241	0	0	**1 241**
Other	293	0	0	**293**	22 079	0	0	**22 079**	12 304	0	0	**12 304**
Total	**1 035**	**566**	**0**	**1 600**	**56 151**	**30 411**	**0**	**86 563**	**91 476**	**48 104**	**0**	**139 580**

Table C-2: Mass balance for (b) Sorting, recycling and biogenic treatment (composting or AD; tpa)

	Calvinia				**GRDM**				**eThekwini**			
Waste Fraction	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**
Biogenic	106	0	422	**528**	5 294	0	21 176	**26 470**	13 181	0	52 724	**65 905**
Glass	40	160	0	**200**	1 435	5 741	0	**7 176**	2 283	9 133	0	**11 416**
Metal	13	51	0	**64**	590	2 359	0	**2 949**	1 359	5 438	0	**6 797**
Paper and Cardboard (Mixed)	42	169	0	**212**	2 649	10 596	0	**13 245**	4 524	18 098	0	**22 622**
Rec Plastic (Mixed)	46	185	0	**231**	2 929	11 715	0	**14 643**	3 859	15 436	0	**19 295**
Non Rec Plastic	73	0	0	**73**	0	0	0	**0**	1 241	0	0	**1 241**
Other	293	0	0	**293**	22 079	0	0	**22 079**	12 304	0	0	**12 304**
Total	**613**	**566**	**422**	**1 600**	**34 976**	**30 411**	**21 176**	**86 563**	**38 752**	**48 104**	**52 724**	**139 580**

Table C-3: Mass balance for (c) the pyrolysis of plastic waste (tpa)

	Calvinia				**GRDM**				**eThekwini**			
Waste Fraction	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**
Biogenic	528	0	0	**528**	26 470	0	0	**26 470**	65 905	0	0	**65 905**
Glass	40	160	0	**200**	1 435	5 741	0	**7 176**	2 283	9 133	0	**11 416**
Metal	13	51	0	**64**	590	2 359	0	**2 949**	1 359	5 438	0	**6 797**
Paper and Cardboard (Mixed)	42	169	0	**212**	2 649	10 596	0	**13 245**	4 524	18 098	0	**22 622**
Rec Plastic (Mixed)	46		185	**231**	2 929	0	11 715	**14 643**	3 859	0	15 436	**19 295**
Non Rec Plastic	15		58	**73**	0	0	0	**0**	248	0	993	**1 241**
Other	293	0	0	**293**	22 079	0	0	**22 079**	12 304	0	0	**12 304**
Total	**977**	**381**	**243**	**1 600**	**56 151**	**18 696**	**11 715**	**86 563**	**90 484**	**32 668**	**16 429**	**139 580**

Table C-4: Mass balance for (d) pyrolysis of plastic waste and biogenic treatment (composting/AD; tpa)

	Calvinia				**GRDM**				**eThekwini**			
Waste Fraction	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**	**Landfill (tpa)**	**Recycle (tpa)**	**Treatment (tpa)**	**Total (tpa)**
Biogenic	106	0	422	**528**	5 294		21 176	**26 470**	13 181	0	52 724	**65 905**
Glass	40	160	0	**200**	1 435	5 741	0	**7 176**	2 283	9 133	0	**11 416**
Metal	13	51	0	**64**	590	2 359	0	**2 949**	1 359	5 438	0	**6 797**
Paper and Cardboard (Mixed)	42	169	0	**212**	2 649	10 596	0	**13 245**	4 524	18 098	0	**22 622**
Rec Plastic (Mixed)	46	0	185	**231**	2 929	0	11 715	**14 643**	3 859	0	15 436	**19 295**
Non Rec Plastic	15	0	58	**73**	0	0	0	**0**	248	0	993	**1 241**
Other	293	0	0	**293**	22 079	0	0	**22 079**	12 304	0	0	**12 304**
Total	**554**	**381**	**665**	**1 600**	**34 976**	**18 696**	**32 891**	**86 563**	**37 760**	**32 668**	**69 153**	**139 0**

C.2. Calculation of recyclate price

Recyclate prices were only available for 2012, as expressed in Table 2-15 for various BBCs in the country. The average of the price from all locations was taken to provide a national average used for calculations. The average price was then converted from R/kg to R/t. In order to provide a more current assumption, the values were escalated using two methods: PPI and CEPCI.

The recyclate price is an example of the calculations used to develop Table 3-4.

Using the PPI Item PPD36000 (recycling and manufacturing), the average PPI for the year 2010 was obtained (69.05) relative to the year 2012 (100) (StatsSA, 2021). For the same item in the time series starting in 2012, a monthly average of 70.09 was obtained for 2012, relative to 2020 (100).

The year adjustment of the recyclate costs quoted for 2012 was similarly calculated (where RC = Recyclate Cost in 2012):

Cost of item in 2020, adjustment from 2012 = $\frac{\mathrm{RC}*100}{70.09}$.

For comparison, the costs in 2020 were also determined using the CEPCI, with CEPCI of 2010 = 550.8; 2012 = 584.6 and 2020 = 596.2; and

Cost (2020) = $\frac{\text{Price (reference year)}*\text{CEPCI (2020)}}{\text{CEPCI (reference year)}}$.

Both recyclate and sorting costs were inflated to provide a current representation of these costs, resulting in the data presented in Table 3-5.

Furthermore, the EPR implementation resulted in PROs providing an EPR fee for certain waste streams. Such an example is PETCO, which provided the indicative fee for certain plastic waste streams as presented in Table C-5.

Table C-5: Current post-consumer waste stream fee, applicable until 31 December 2021 (PETCO, 2021)

Post-consumer waste streams (i.e. identified products)	Current indicative 2021 EPR fee (R/t)
PET bottles – beverage / Plastic PET beverage bottles	R565
PET bottles – home & personal care / Single-use PET products	R565

Post-consumer waste streams (i.e. identified products)	Current indicative 2021 EPR fee (R/t)
PET bottles & jars – food / Single-use PET products	R565
PET Bottles – edible oil / Plastic PET oil bottles	R565
Thermoform PET / Plastic PET thermoformed	R565
HDPE closures / Single-use HD products	R565
PP closures / Single-use PP products	R565
BOPP, PP, PE wraparound labels / Polyolefins flexibles	R565
Other self-adhesive labels	R565
PET shrink sleeves / Plastic PET flexibles	R2500

The 2021 indicative fee estimated the percentage increase in the plastic streams price between 2012 and 2021. The mixed plastic stream was R543.75/t in 2012 (Viljoen et al. (2012)), while the price of all plastic waste streams except PET shrink sleeves/plastics PET flexibles is R565 in 2021. Therefore, these two values will determine the percentage change in cost. The calculation method is as follows:

$$\%\ \text{change} = \frac{\text{Price}_{\ 2021} - \text{Price}_{\ 2012}}{\text{Price}_{\ 2012}} \times 100$$

$$\%\ \text{change} = \frac{565.00 - 543.75}{543.75} \times 100 = 3.91\%$$

The 3.91% increase was applied to all recyclate costs, which was used as a discussion point in the sensitivity analysis.

C.3. Calculations of biogas and energy and electricity potential

The amount of electricity produced was based on assumptions according to literature: the amount of volatile solids in dry waste was 0.88, the biogas production was assumed at $0.936\,\frac{\text{m}^3}{\text{kg}}$, the energy content of biogas was 20.7 MJ/m^3, the energy conversion efficiency was 36%, and the conversion of electricity using CHP was 35% (AEBIOM European Biomass Association, 2008; Gogela et al.,2017)).

$$\begin{aligned}\text{Biogas potential by AD} &\\ &= \text{amount of volatile solid in dry food waste} \\ &\times \text{biogas production from volatile solid by AD} \\ &= (0.88 \times \text{feed organic})\ \text{kg} \times 0.936\,\frac{\text{m}^3}{\text{kg}}\end{aligned}$$

One cubic meter of biogas contains about 20.7 MJ of energy.

$$\text{Energy potential of biogas} = \text{biogas potential } \times \text{unit energy potential of biogas}$$
$$= \text{biogas potential m}^3 \times 20.7\ \frac{\text{MJ}}{\text{m}^3}$$

$$\text{Electricity potential} = \text{energy potential } \times \text{conversion efficiency} = \text{energy potential } \times 0.36$$

Finally, assuming that the CHP system efficiency is 35%, the total annual amount of electricity is calculated

$$\text{Electricity} = \text{electricity potential } \times \text{conversion efficiency}$$
$$= \text{electricity potential } \times 0.35$$

C.3. Fractions of plastics and paper

Table C-6: Fractions of different plastic and paper-based on GreenCape (2020) material circulation

Waste Fraction	Individual Material	Material in Circulation (Virgin/Recyclate) (tons)	Percentage of individual material relative to the waste fraction in circulation
Plastics	PET (beverage bottles)	157 760	18%
	PET (thermo-form/edible oil)	74 240	8%
	LDPE	332 163	37%
	HDPE	133 435	15%
	PP	143 374	16%
	PVC	12 937	1%
	PS	34 023	4%
	Total	**887 932**	
Paper and Cardboard	Paper	952 739	45%
	Cardboard	1 160 204	55%
	Total	**2 112 943**	

The material balance will therefore look as follows:

Table C-7: Mass of different waste streams by applying the above assumptions for EPR (in tpa)

	Percentage (from Table C-6)	Calvinia	GRDM	eThekwini
Biogenic		422	21 176	52 724
Glass		160	5 741	9 133
Metal		51	2 359	5 438
Paper and Cardboard (Mixed)		169	10 596	18 098
Paper	0,45	76	4 768	8 144
Cardboard	0,55	93	5 828	9 954
Plastic (Mixed)		185	11 715	15 436
PET (beverage bottles)	0,18	33	2 081	2 743
PET (thermo-form/edible oil)	0,08	15	979	1 291
LDPE	0,37	69	4 382	5 774
HDPE	0,15	28	1 760	2 320
PP	0,16	30	1 892	2 492
PVC	0,01	3	171	225
PS	0,04	7	449	591
Non Rec Plastic		0	0	0
Other		293	17 663	10 836
Total		**1 280**	**69 250**	**111 664**

C.4. Cost allocation

The costs are represented by a negative value (-), while credits are represented by positive values. The overall cost/credit is the credits (landfill credit +sales recyclate) less the costs/expenses (sorting + transport of recyclates).

Table C-8: Cost allocation for biogenic processes (composting and AD) for Calvinia

Waste stream	Sorting (R/a)	Landfill Credit (R/a)	Transport Recyclate (R/a)	Sales Recyclate (R/a)	Total (R/a)
Biogenic	-74 825	246 532			171 707
Glass	-28 360	93 440	-104 960	45 008	5 128
Metals	-9 075	29 901	-33 587	37 197	24 435

Waste stream	Sorting (R/a)	Landfill Credit (R/a)	Transport Recyclate (R/a)	Sales Recyclate (R/a)	Total (R/a)
Paper and cardboard	-30 016	98 897	-111 090	66 129	23 920
Recyclable Plastics	-32 784	108 017	-121 334	123 035	76 934
Non Recyclable Plastics	-10 436				-10 436
Others	-41 519				-41 519
Total	-227 016	576 786	-370 971	271 369	250 169

Table C-9: Cost allocation for the biogenic treatment processes for GRDM

	Sorting (R/a)	Landfill Credit (R/a)	Transport Recyclate (R/a)	Sales Recyclate (R/a)	Total (R/a)
Biogenic	-3 753 429	12 366 729			8 613 300
Glass	-1 017 600	3 352 770	-3 875 205	1 614 956	74 921
Metals	-418 195	1 377 860	-1 592 561	1 714 068	1 081 172
Paper and cardboard	-1 878 141	6 188 066	-7 152 302	4 137 739	1 295 361
Recyclable Plastics	-2 076 435	6 841 399	-7 907 439	7 792 635	4 650 160
Non Recyclable Plastics	0				0
Others	-3 130 776				-3 130 776
Total	-12 274 577	30 126 824	-20 527 507	15 259 397	12 584 138

Table C-10: Cost allocation for biogenic process for eThekwini

	Sorting (R/a)	Landfill Credit (R/a)	Transport Recyclate (R/a)	Sales Recyclate (R/a)	Total (R/a)
Biogenic	-9 345 341	21 985 937			12 640 596
Glass	-1 618 758	3 808 306	-4 109 683	2 569 008	648 873
Metals	-963 824	2 267 500	-2 446 943	3 950 453	2 807 187

	Sorting (R/a)	Landfill Credit (R/a)	Transport Recyclate (R/a)	Sales Recyclate (R/a)	Total (R/a)
Paper and cardboard	-3 207 791	7 546 679	-8 143 899	7 067 094	3 262 084
Recyclable Plastics	-2 736 057	6 436 874	-6 946 266	10 268 125	7 022 675
Non Recyclable Plastics	-175 931				-175 931
Others	-1 745 696				-1 745 696
Total	-19 792 472	42 045 296	-21 646 791	23 854 682	24 460 715

The feedstock cost considers the credit stream of interest in respect to the weight based allocation of the landfill of "others" to feedstock and recyclate. The calculations are explained as follows for the biogenic processes:

$$F_{bio} = S_{bio} + \left(\frac{M_{bio}}{(M_{bio} + M_{recyclates})}\right) \text{ x } S_{other}$$

where F_{bio} = biogenic feedstock cost; S_{bio} = biogenic fraction separation costs; S_{other} = "other" fraction separation cost; M_{bio} = mass of biogenic fraction (separated); and $M_{recyclates}$ = sum of the masses of the recyclate fractions (separated)

Consider the biogenic treatment for Calvinia:

$$F_{bio} = (\text{R}171\ 707) + \frac{422}{(160 + 51 + 169 + 185 + 422)} \text{ x } (\text{-R}51\ 95) = \text{R}149\ 500$$

$$F_{recyclates} = S_{recyclates} + \frac{M_{recylates}}{(M_{bio} + M_{recyclates})} \text{ x } S_{other}$$

where $F_{recylate}$ = recyclates cost; $S_{recyclates}$ = sum of the recyclate fractions' separation costs; S_{other} = "other" fraction separation cost; M_{bio} = mass of biogenic fraction (separated); and $M_{recyclates}$ = sum of the masses of the recyclate fractions (separated)

For Calvinia:

$F_{recyclates}$ = R5 128+R24 435+R23 920+R76 934 + $\frac{(160 + 51 + 169 + 185)}{(160 + 51 + 169 + 185 + 422)}$ x (-R51 956) = R100 669

These calculations were similarly performed for all locations and treatment options.

Table C-11: Summary of cost allocation results for biogenic processes

	Calvinia	GRDM	eThekwini
Feedstock cost, including allocated waste costs (R/a)	149 500	7 328 151	11 635 756
Recyclate revenue, including allocated waste costs (R/a)	100 669	5 255 987	12 824 032
Waste diverted (tpa)	988	51587	100828
Landfill credits (R/a)	576 786	30 126 824	42 045 296
Waste diverted (%)	61.72	59.59	72.24

Table C-12: Summary of cost allocation results for pyrolysis of plastic waste

	Calvinia	GRDM	eThekwini
Feedstock cost, including allocated waste costs (R/a)	53 746	2 113 087	168 934
Recyclate revenue, including allocated waste costs (R/a)	-17 425	-1 780 874	-778 049
Waste diverted (tpa)	624	30411	49097
Landfill credits (R/a)	364 640	17 760 095	20 473 256
Waste diverted (%)	39.02	35.13	35.17

Table C-13: Summary of cost allocation results for combination scenarios

	Calvinia	GRDM	eThekwini
Feedstock cost, including allocated waste costs (R/a)	236 140	11 382 157	15 322 180
Recyclate revenue, including allocated waste costs (R/a)	46 713	1 316 784	6 229 647
Waste diverted (tpa)	988	51587	100 828
Landfill credits (R/a)	576 786	30 126 824	42 045 296
Waste diverted (%)	61.73	59.60	72.24